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BRITTLE MATERIALS DESIGN, HIGH TEMPERATURE GAS TURBINE

Technical Report By:

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Final Report

Contract Number DAAG 46-71-C-0162

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Prepared for

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ABSTRACT

A highlight summary of the work conducted by Westinghoue from July 1971 to June 1976, on the Defense Advanced Research Projects Agency (DARPA) sponsored program, "Brittle Materials Design, High Temperature Gas Turbines," is presented. The Westinghouse portion of the program entitled, "Stationary Turbine Project," was concerned with the development of ceramic design and materials technology for large, electric, power-generating, combustion turbines. Major incentives for the use of ceramic components in these turbines include significant improvements in the overall efficiency of power conversion through higher operating temperatures and minimum cooling requirements and extended component life through greater resistance to corrosion/erosion with a variety of fuels.

The first stage ceramic stator vane with associated support hardware was chosen as the principal developmental objective. A test demonstration of design concepts and materials feasibility was achieved in a high temperature static rig at a peak vane temperature of 2500°F. Two series of 100 duty cycle testing to represent peaking turbine operation at 0.8 turbine simulation were performed at 2200 and 2500°F, respectively. The three piece vane assembly design concept was confirmed as viable and hot pressed silicon nitride emerged as the best candidate ceramic material for structural turbine applications.

A brief presentation of program background that includes a description of the general development approach and iterative plan of program execution is followed by technical highlights under the two major, interacting program tasks; Material Technology consisting of engineering properties, materials science and non-destructive evaluation (NDE), and Component Development consisting of design and analyses, fabrication, NDE, testing and failure analysis.

Conclusions and recommendations for future ceramic-related turbine developments are discussed.

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FOREWORD

The Stationary Gas Turbine Project represents the Westinghouse contribution to the Defense Advanced Research Project Agency (DARPA) sponsored "Brittle Material Design, High Temperature Turbine" program, Order Number 1849, Contract Number DAAG-46-71-C-0162.

The final report is presented in four volumes as follows:

Volume I - Program Summary

Volume II - Ceramic Stator Vane Development

Volume III - Rotor Blade Development and Turbine Modification

Volume IV - Materials Technology

Final results of static rig testing and analysis for the tenth semi-annual report period are included as part of this final report which represents a comprehensive project review summarizing the activities from July 1, 1971 to June 30, 1976.

Westinghouse performed this work under subcontract to the Ford Motor Company, prime contractor for the Defense Advanced Research Project Agency. The Army Material and Mechanics Research Center (AMMRC) at Watertown Arsenal, Watertown, Massachusetts, served as Program Monitor for DARPA.

The program's overall Principal Investigator was Mr. A. F. McLean, who also served as Program Manager for the Ford Vehicular Turbine Project.

Dr. R. J. Bratton was Principal Investigator and Program Manager for Westinghouse. Mr. D. G. Miller served as Project Engineer. Mr. A. N. Holden, now deceased, functioned as Project Manager at Westinghouse Generation Systems Division from July 1, 1971 to May 1, 1975. Mr. G. Levari succeeded Mr. Holden with Mr. C. R. Booher, Jr, accepting responsibility for design, analysis and rig testing for the Division at that time.

Westinghouse wishes to acknowledge the efforts of the following personnel who contributed to the program:

1. Dr. Maurice J. Sinnott who conceived and started the program when he was at DARPA in 1971.

2. DARPA - for support of the program. Dr. E. Van Reuth and Dr. M. Stickley for their interest and support.

3. AMMRC - for monitoring the program. Dr. E. S. Wright, who replaced Dr. A. E. Gorum (presently retired) as Technical Monitor, and Drs. R. N. Katz, E.N. Lenoe and H. Priest.

4. Ford Motor Co. - A. F. McLean, T. W. McLaughlin, E. A. Fisher, P. Berry, R. R. Baker and A. Paluszny.

The final report was prepared and edited by D. G. Miller and R. J. Bratton with editing assistance from E. J. Phillips. Contributions to the final report were made by C. R. Booher, Jr., S. C. Singhal, F. F. Lange, W. Van Buren and E. S. Diaz.

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This final report is dedicated to A. N. Holden.

EXECUTIVE SUMMARY

Beginning in mid-1971, the Defense Advanced Research Projects Agency initiated the DARPA/Ford/Westinghouse program entitled, "Brittle Materials Design - High Temperature Gas Turbine," under contract DAAG46-71-C-0162. DARPA's major program goal was to prove by practical demonstration that efforts in ceramic design, materials, fabrication, testing and evaluation could be drawn together and developed to establish the usefulness of brittle materials for an important engineering application.

The plan for the Ford Vehicular Turbine Project was to develop an entire ceramic hot flow path, including the highly stressed turbine rotors, for a small vehicular turbine of about 200 HP[1]. Demonstration of this objective by 200 hours of operation over a representative duty cycle at turbine inlet temperatures of up to 2500°F was also required.

The Westinghouse portion of this program, entitled, "Stationary Turbine Project," was concerned with the application of ceramics in large, electric-power-generating, combustion turbines. Significant improvements in the performance of these machines depend upon high operating temperatures with minimum component cooling. The ability of the turbine components to withstand hot corrosion and erosion is important also. The advantage of uncooled ceramic components, compared to the conventional use of highly cooled superalloys, is significantly improved efficiency and power output even if turbines are made to operate with corrosive fuels. Successful development of ceramic design and materials technology could lead to large combined cycle (combustion/steam) power plants which operate at 50 percent thermal efficiency using fuel derived from coal. This would represent a dramatic increase over today's best power plants at 42 percent efficiency.

The principal objective chosen for the Stationary Turbine Project at Westinghouse was the development of first-stage ceramic stator vanes with associated support hardware and their demonstration in a 30 Mw frame-size test turbine for 100 duty cycles of peaking operation from a vane hot spot temperature of 2500°F. When this proved too formidable for the DARPA 5-year program, the objective was revised in 1974 to conclude that program by demonstrating the vanes in a high temperature static rig that had been constructed to proof test vanes prior to the actual turbine test. This revised objective was achieved and demonstrated successfully. While ceramic vanes are considered feasible for large industrial gas turbines, much remains to be accomplished before a state of technological readiness is reached.

In this initial ceramic turbine technology program considerable progress was made toward meeting the overall objective of applying ceramics in large industrial turbines. Candidate materials, Si_3N_4 and SiC, were identified and the best available commercial grades were characterized and improved significantly. Ceramic components were designed and process developments led to the fabrication of high-strength ceramic vanes that

were tested with very encouraging results. The baseline technology needed for future work was developed.

The Stationary Turbine Project was organized into two principal tasks: Component Development and Materials Technology. In the program summary that follows, the progress made in these areas is reviewed. In addition, conclusions reached from the work and recommendations for future work required to achieve technological readiness are given.

This Program Summary is the first of four volumes that will be issued as the final report of work completed on the DARPA/Westinghouse Stationary Turbine Project.

Outstanding highlights that trace progress in the program over the period July 1971 to June 1976 were as follows:

August 1971 - The first generation design of a unique three-piece ceramic first-stage stator vane consisting of an airfoil and two end caps, fundamentally different from its metal counterpart, was completed. Drawings were submitted for fabrication of the parts.

May 1972 - The feasibility of fabricating the three-piece industrial-size, ceramic turbine vanes by hot pressing and machining methods was demonstrated.

March 1973 - The first industrial-size, prototype Si_3N_4 vanes were manufactured for cyclic testing from a peak (hot spot) temperature of 2200°F in a simulated (static rig) turbine environment.

June 1973 - A highly instrumented static rig was constructed and made ready to test the ceramic vane assemblies at 2200°F.

July 1973 - A full-scale kinematic model of the three-piece ceramic vane assembly and associated hardware demonstrated the mechanical integrity of the design concept.

September 1973 - 2200°F cyclic testing of the ceramic vane assembly was successfully completed. This milestone represented the first test of full-size ceramic vanes for industrial turbine use. The results provided the incentive to proceed to 2500°F testing.

July 1974 - The third generation design of the three-piece vane featuring a tapered-twisted airfoil and modified end caps was completed. Drawings were submitted for fabrication of these parts.

July 1974 - The static rig was modified and made ready to test the vane assemblies at 2500°F.

September 1974 - Semiproduction machining methods using drum cam milling technology were demonstrated for the production of Si_3N_4 vane airfoils. The result was a significant cost reduction ($\sim$70 percent) for vane manufacturing and improved surface finish.

October 1974 - A combustor failure in the static rig during initial 2500°F testing showed that Si_3N_4 vanes do not necessarily fail catastrophically under highly adverse conditions even when spattered with molten metal.

May 1975 - Static rig modifications for fail-safe operation at 2500°F were completed.

October 1975 - Final cyclic testing of Si_3N_4 vane assemblies from a peak (hot spot) temperature of 2500°F was initiated.

March 1976 - The program test demonstration objective of 100 duty cycles of peaking-type operation from a vane hot spot temperature of 2500°F was completed with very encouraging results.

July 1976 - A detailed analysis of the 2500°F static rig tests using actual test boundary conditions was completed.

In addition to the above highlights related to the first row stator vane, a parametic analysis of a ceramic rotor blade was conducted. A preliminary blade design was analyzed subsequently in more detail, using three-dimensional finite element stress analysis techniques. This work has been continued under sponsorship of the Electric Power Research Institute (Contract RP421-1).

Materials technology formed a basis for component development throughout the program. Determination of engineering properties, which characterized candidate materials (Si_3N_4 and SiC), helped to make the design codes more comprehensive. Materials science investigations made it possible to understand property behavior and relate it to processing and microstructures. The development of NDE techniques for ceramics permitted the detection and characterization of life limiting flaws. Materials technology at Westinghouse also paved the way for significant improvements (over 400 percent) in the properties of the commercial grade materials, and was largely responsible for the development of Norton NC132 Si_3N_4 which evolved from the initially available but not totally HS110 material.

More recently, materials technology at Westinghouse led to the development of high purity Si_3N_4 powder and new Si_3N_4 compositions which exhibited improved high temperature creep and oxidation resistance. Both represent major advances in material improvement.

The significant conclusions and recommendations for future work are outlined in Sections 2 and 3 of the Program Summary which follow . Most significantly, results do not preclude the future use of ceramics in stationary combustion turbines. Evidence suggests potential improvement of material properties will permit the development of static component hardware at least.

SECTION 1

PROGRAM RESUTLS

1.1 INTRODUCTION

As stipulated by the Defense Advanced Research Projects Agency, the major purpose of this program was the demonstration of brittle materials in demanding high temperature structural applications. DARPA's major program goal was to show proof by a practical demonstration that efforts in ceramic design, materials, fabrication, testing, and evaluation could be drawn together and developed to establish brittle materials for engineering use. The turbine engine, utilizing uncooled ceramic components in the hot flow path, was chosen as the vehicle for this demonstration.

Progress has been and continues to be closely related to the development of high temperature, corrosion resistant materials. Since the early days of the jet engine, new alloys have evolved to permit gradual increases in the temperature of operation. Nickel/chromium superalloys are used, today, where metal temperatures approach 1650° to 1800°F. However, there is considerable incentive to increase the turbine inlet temperature still further in order to improve specific air and fuel consumptions. A turbine engine with ceramic components promises to represent a major step in the attainment of a 2500°F turbine inlet temperature objective. Such an engine offers significant advantages in efficiency, power, cost and exhaust emissions as well as materials and fuel utilization.

These advantages address many of the nation's energy related problems directly and meet many critical needs of the Department of Defense. Requirements for future Army vehicular prime movers emphasize increased fuel efficiency, increased specific power and wide fuel tolerance. The Army's turbine-powered, mobile-field generators share these goals and require significant improvement in erosion resistance. Similar advantages are projected for marine applications of a ceramic turbine. Limited life engines for RPV's and drones are expected to achieve higher performance at lower cost if ceramic components are employed. It was appropriate, therefore, that DARPA initiate a major program to demonstrate and encourage the use of ceramic materials and brittle materials design aimed at the turbine engine.

In this, the final report on the DARPA/Ford/Westinghouse Stationary Gas Turbine Project, Final results from the 2500°F static rig test demonstration conducted during the tenth semiannual report period are presented as part of a comprehensive project review which summarizes the activities on this contract from July 1, 1971 to June 30, 1976.

1.2 STATIONARY TURBINE BACKGROUND

The Westinghouse program has been concerned with the development of ceramic technology for large stationary combustion turbines used for central station electric power generation. These turbines, which produce 30 to 90 MW of power, have been used by utilities for the past decade to supplement their steam turbines for quick peaking and black-start capability. Figure 1-1 shows a longitudinal section of the Westinghouse W251, 30 MW turbine. In this simple cycle machine, air is induced through a large intake silencer and filtered into an 18-stage axial compressor before entering the combustor housing. Compressed air at 650°F is supplied to combustion cans assembled in a circumferential array, mixed with fuel and ignited in the primary combustion zone. The gas passes downstream through the combustor section, through the transition zone and enters the turbine at the inlet gas temperature. The hot gases expand through the three-stage turbine section and exhaust through a stack. This operation is based on the well-known Brayton Cycle, wherein the higher the operating temperature of the gas at the turbine inlet, the greater the work a given unit can perform with each pound of working fluid, and the greater the overall cycle efficiency. Today's simple-cycle turbines, operating at an average inlet temperature of 2000°F, attain efficiencies of about 28 percent.

Power plant systems based upon a combined combustion/steam turbine cycle meet the generalized requirements of intermediate load power generation quite well. Theoretically achievable increases in cycle efficiency, however, could conceivably make them competitive in base load service. In this type of plant application residual heat, noramlly lost from the gas turbine exhaust, is extracted by a recovery boiler and used to generate steam. Westinghouse PACE installations, for example, are designed to develop 260 MW from two W501 combustion turbines and a single steam turbine generator combined in this manner. Here cycle efficiency approaches 42% at 2000°F, gas turbine inlet temperature.

Future improvements in combined cycle systems are destined to bome from the combustion turbine side since steam turbine performance is near peak efficiency following over 70 years of development. The advantages of higher steam temperatures or even super-critical steam systems are expected to be affected by very large increases in the cost of materials and the projected costs of operation and maintenance. The effect of higher combustion turbine inlet temperature on combined cycle effeciency can be appreciated best from Table 1-1. Thermal efficiencies exceeding 48% are achievable in the conversion of heat to electricity at 2500°F turbine inlet temperature.

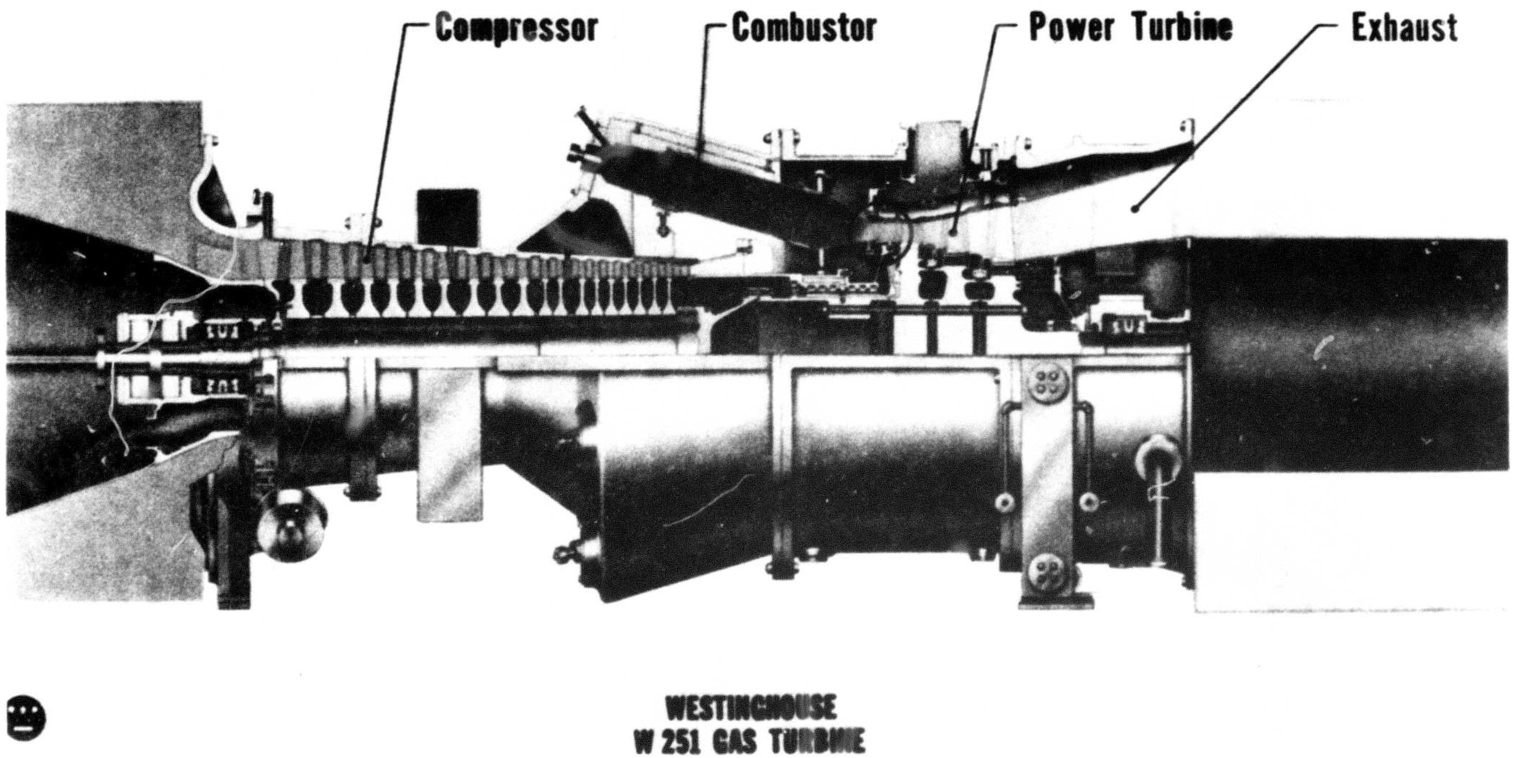

Figure 1-1. Westinghouse W251 Gas Turbine

TABLE 1-1

COMBINED CYCLE PERFORMANCE
(Constant Frame Size)

Inlet Temperature (°F)	2000°F	2500°F	3000°F
Efficiency (%)	42	49	52
Power (MW)	300	480	640

In practical systems, the attainment of high thermal efficiency by increasing temperature and minimizing cooling flow usage becomes difficult above 2000°F operating temperature limitations of metals. Even at a 2000°F operating temperature, the metal components must be cooled internally to operate at a maximum of 1650°F, above which accelerated hot corrosion/erosion effects on vanes and blades dominate performance. Thus, if higher inlet combustion temperatures are used with metal designs, either greater coolant flow or more efficient cooling media are required to keep metal components below critical temperatures. In general, all cooling schemes needed for the survival of metal in turbines must use part of the abailable energy to remove heat from high temperature locations. This imposes efficiency penalties directly.

The major advantage of ceramics is their potential capacity for operation at turbine inlet temperatures and in corrosion/erosion environments that far exceed the capability of any uncooled alloy system. The major drawback of ceramics is brittleness. In order to guarantee the eventual engineering use of ceramics in industrial turbines, brittle design technology, material technology and design verification methods must be developed and woven into a coherent combustion turbine ceramic technology. The DARPA program represented an important first step in this endeavor.

The ultimate goal for the future is to make the best use of ceramics in an efficient combined cycle plant that utilizes coal-derived fuels. If successful, huge national benefits can be derived through the conservation of both fuel and capital with acceptably low environmental impact.

Figure 1-2 shows a preliminary conceptual version of the Westinghouse 251, 30 MW turbine which would serve to demonstrate the viability of ceramics in meeting the goal described above. It includes a ceramic hot wall combustor, ceramic first-stage stator vanes, ceramic first-stage rotor blades, ceramic second-stage rotor blades, ceramic second-stage vanes and ceramic shrouds. Ceramic parts are marked "C." The first-stage vane has been developed in this DARPA program. The first-stage rotor

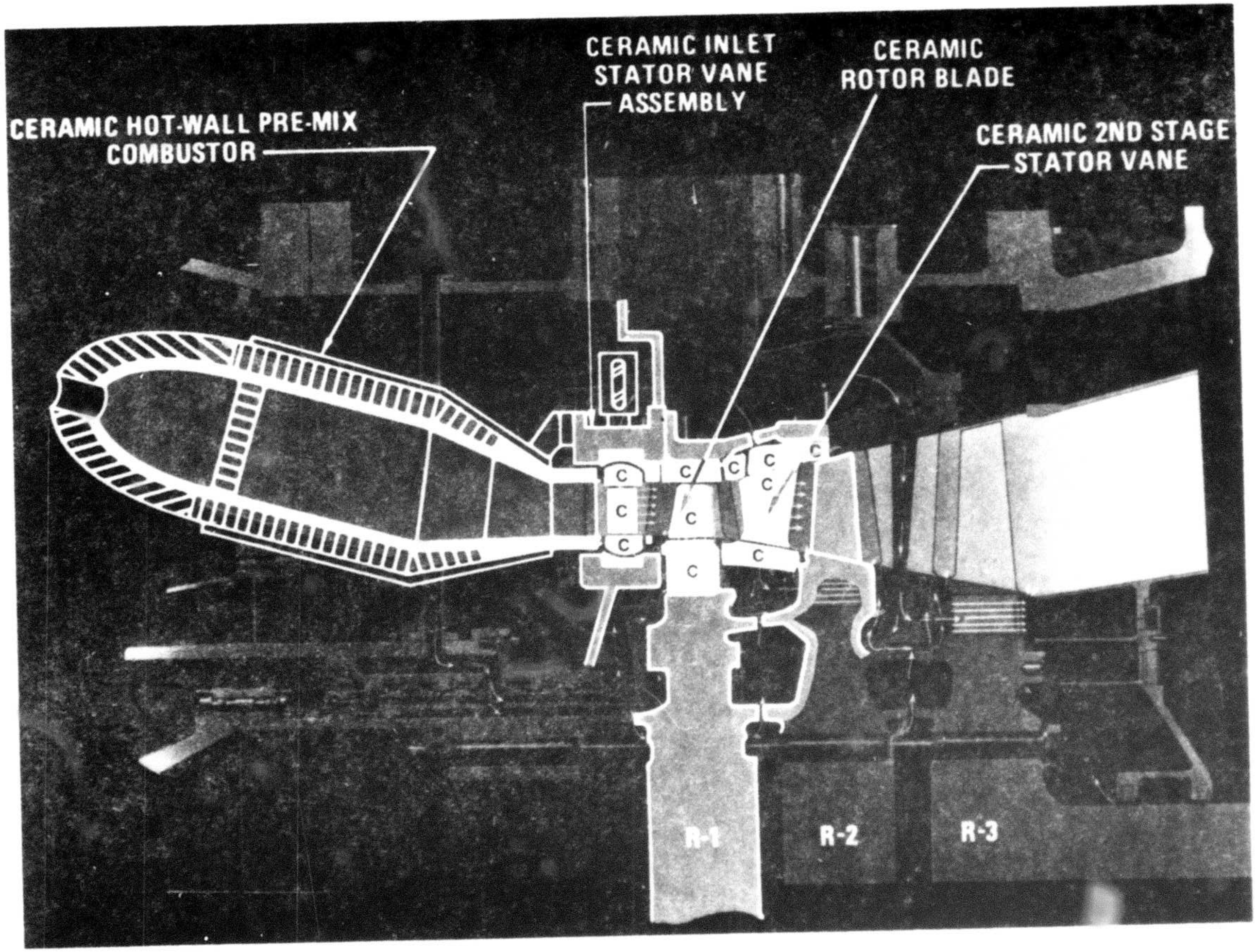

Figure 1-2. Conceptual Ceramic Turbine for Power Generation

blade attachment designs and second-stage cantilevered vane attachment designs are subjects of ongoing work funded by the Electric Power Research Institute.[17,18,19] Descriptions of further developments needed to bring ceramic components to a state of technological readiness and engine demonstration have been brought to the attention of the Energy Research and Development Administration.

1.3 EXPERIENCE AND PROJECT PLAN

1.3.1 EXPERIENCE

In 1965 Westinghouse initiated a program to exploit the high temperature capabilities of ceramics in industrial turbines. Figure 1-3 displays program areas conducted prior to mid-1971 when the DARPA program was initiated to accelerate these development efforts. Beginning with programs focused to understand the mechanical and thermal behavior of brittle materials subjected to complex loads, work progressed to where an assessment of potential materials and components could be made. Based on known turbine cycle performance rewards with increasing temperature, the initial target inlet temperature selected for ceramic application was 2500°F. The areas of the industrial turbine selected for possible ceramic applications were, in order of increasing difficulty, the combustor, stationary vanes and rotating blades. Material families selected for screening were high strength oxides, nitrides and carbides.

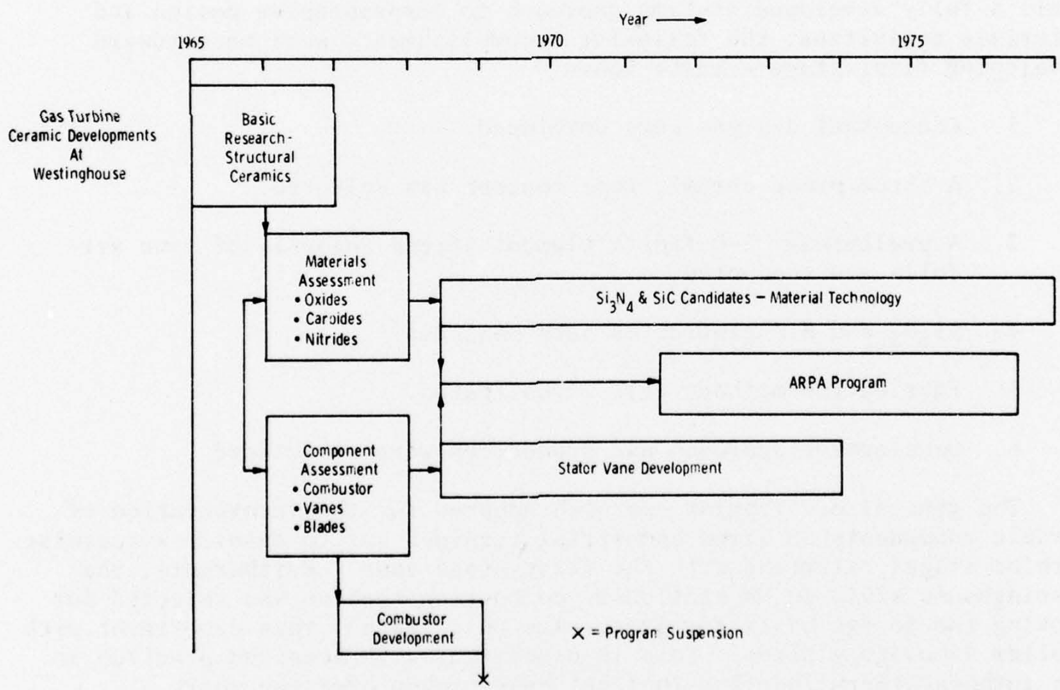

Figure 1-3. Stationary Turbine Project Background Chart

The design and testing of a ceramic-lined combustor, using reinforced castable ceramic materials, was the earliest study of a ceramic application to industrial turbines. Test results showed that the concepts appeared feasible, but further development was curtailed because new combustors were considered less critical to much-improved turbine performance than first-row vanes. At the time, metal combustor designs were capable of operating at much higher temperatures than the downstream first-stage vanes could sustain. Development efforts were redirected accordingly.

Materials research and development was conducted over a period of about 2 years, whereby Si_3N_4 and SiC emerged as the leading candidates for the gas turbine vane application. Having selected the material candidates and the vane application, brittle material design questions came to the forefront. Westinghouse then decided that brittle material design "thinking" was a necessary requirement for further development and adopted the beginnings of parallel and interacting design and materials efforts. Prior to the onset of the DARPA program, which made possible a fully developed systems approach to comprehensive design and materials activities, the following accomplishments were made toward developing first-stage ceramic vanes:

1. Conceptual designs were developed.

2. A three-piece ceramic vane concept was selected.

3. A preliminary 2-D finite element stress analysis of vane airfoils was conducted.

4. Si_3N_4 and SiC candidates were selected.

5. Fabrication methods were investigated.

6. Development approach and procedures were structured.

The general development approach adopted for the incorporation of ceramic components in large industrial turbines was to develop successive turbine stages, starting with the first-stage vane. Furthermore, the Westinghouse W251, 30 MW stationary combustion turbine was selected for proving the design basis for large-size units rather than experiment with smaller laboratory sizes. This is consistent with accepted practice in the turbomachinery industry that has been proven over the years.

The generalized procedure for turbine component development is shown in Figure 1-4. Parallel efforts in component development and material technology form the basis for iterative development. In this procedure, a preliminary design evolved based on engine aerodynamic and mechanical configuration requirements and the loading history that components must

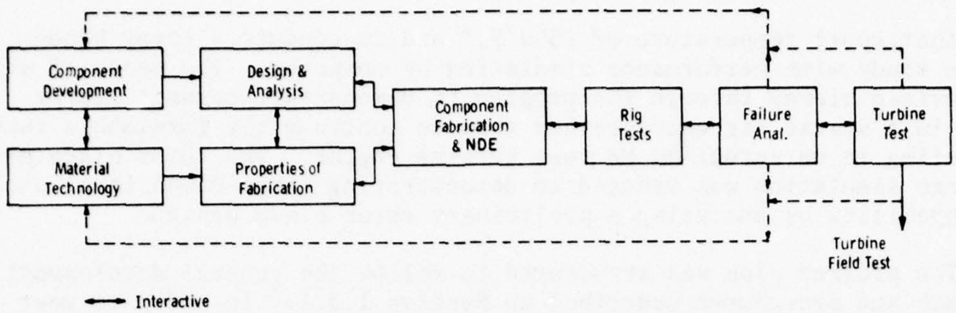

Figure 1-4. Iterative Development Procedure for Industrial Gas Turbine Components

survive. The parts were dimensioned for the engine configuration, and having chosen a candidate material, a preliminary stress analysis was conducted. One-dimensional elastic analysis was used to evaluate the preliminary configuration. Two-dimensional models were then developed to parametrically analyze critical areas. Finally, three-dimensional analyses were performed to obtain local temperatures, stresses and deformations to be used for comparison with the failure properties of the material. Three-dimensional finite element modeling, although relatively new, is recognized as very important for brittle materials design and analysis.

After completing the stress analysis and design refinement, and deciding that the available material property data indicate adequate design integrity, the part was fabricated, inspected by NDE methods and tested to validate analyses. Based on this information, either the part was ready for field testing, or more likely, modifications were needed in materials, design, test modifications or even engine configuration.

It should be noted that the design procedure adopted for ceramic component development is much more inclusive than that practiced for metal component development in the present industrial turbine industry. The reason is that industrial turbine developments have been historically derived from the aricraft industry. Conservative designs using aircraft technology have largely eliminated the need for costly laboratory testing with the exception of combustion. In fact, field operation of these large turbines in cooperation with utility companies is the general means of obtaining durability test data.

1.3.2 DARPA PROGRAM - STATIONARY TURBINE PROJECT PLAN

The principal objectives of the stationary turbine project were to develop first-stage ceramic vanes and demonstrate them in a 30 MW, frame size test turbine for 100 duty cycles of peaking cycle operation from a

peak (hot spot) temperature of 2500°F,* and to conduct a rotor blade design study with performance simulation by computer. The scope of work was revised midway through the program to demonstrate ceramic stator vanes in a static rig only, rather than to continue the formidable task of testing in an actual 30 MW test turbine engine. The rotor blade performance simulation was reduced to demonstrating three-dimensional analysis capability by analyzing a preliminary rotor blade design.

The program plan was structured to follow the general development approach and procedures described in Section 1.3.1. In order to meet the original project objectives, the work was divided into six major tasks that contributed to parallel and interactive efforts in component development and material technology as follows:

1. Stator Vane Development
2. Rotor Blade Development
3. Advanced Turbine Modification
4. Engineering Properties
5. Material Sciences
6. Material Fabrication

The program logic in terms of an iterative development program plan and factors involved is shown in Figure 1-5. From the beginning, the plan was to traverse the iterative loop twice for vane development. The first loop leads to 2200°F static rig testing to verify both vane design and materials capability before proceeding to 2500°F. If successful, the second loop leads to 2500°F static rig testing and provides the basis to either proceed with turbine testing or to redirect the program to solve specific problems. It should be noted that extensive development was required in each of the blocked areas shown in Figure 1-5. For this reason the interaction between factors becomes very complex when fitted to a 5-year program.

All development efforts, by necessity, are conducted in parallel which can lead to serious scheduling problems when unforeseen obstacles occur. Anticipated difficulties were indeed experienced in vane procurement and static rig testing to the extent that the objectives were revised (Figure 1-5).

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*The 2500°F hot-spot vane temperature corresponds to an average turbine inlet temperature of about 2200°F. Temperature profiles with a peak-to-average of ∿300°F are common in today's air-cooled combustors.

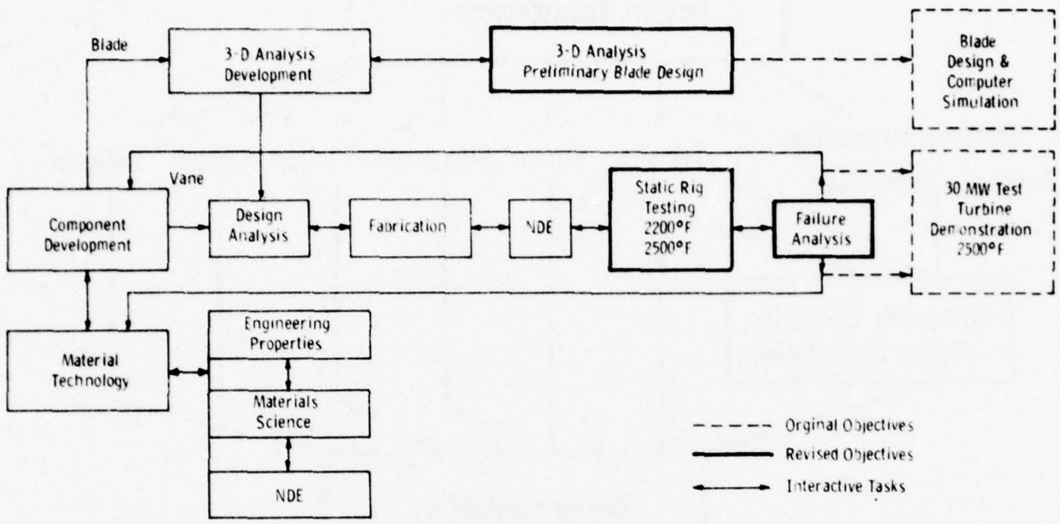

Figure 1-5. DARPA Stationary Turbine Project - Iterative Development Plan

Careful material and design work provided the basis for the stationary turbine project plan. Figure 1-6 shows the interaction between material engineering properties and design. Throughout the program, engineering property determinations were made simultaneously with the design effort. In so doing, material improvements were incorporated into component fabrication and testing to reflect back upon design. Similarly, materials science investigations led to material behavior understanding and thereby a basis for material improvements through composition and process modifications. Nondestructive evaluation (NDE) played an important role by detecting fabrication and component manufacturing defects that could lead to premature failures.

Of the original tasks, Task 2, Ceramic Rotor Blade Development, was discontinued in early 1973 to permit full attention to vane design and static rig testing. However, the work had progressed sufficiently well to begin serious rotor blade development in 1975 through the Electric Power Research Institute.* Task 3, Advanced Turbine Development, proceeded through turbine design modification, but the actual retrofit and testing were too formidable for the DARPA contract and were therefore discontinued in 1975.

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*EPRI Contract RP421-1-SFD-10485-CE

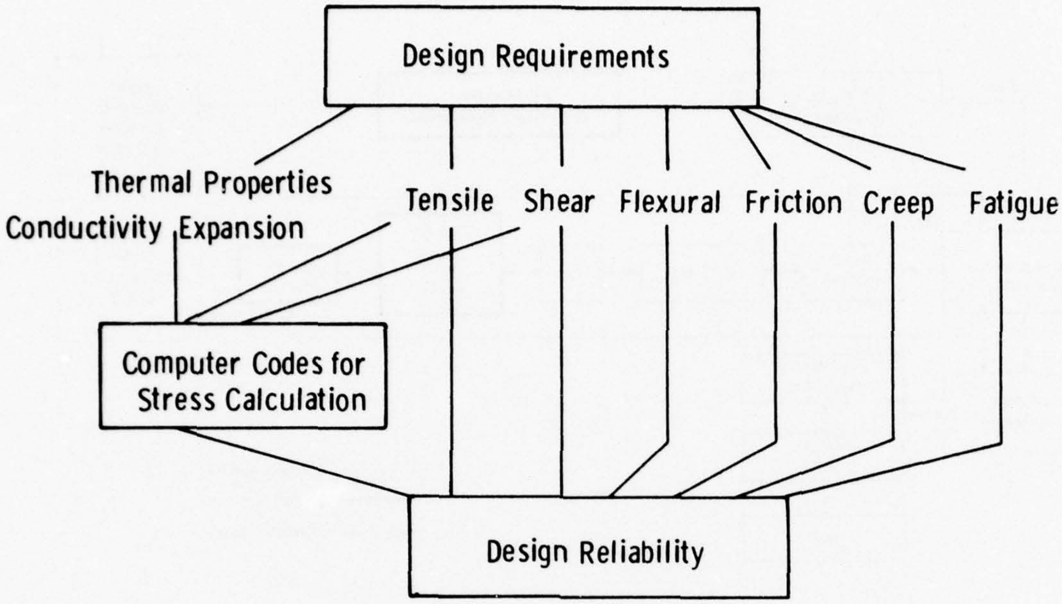

Figure 1-6. Interaction Between Properties and Design

All other tasks were completed. In addition, a modest material development effort was mounted in the latter half of 1975 to address deficiencies in hot pressed silicon nitride. This work is continuing under ERDA sponsorship.*

The Westinghouse Research Laboratories retained overall project responsibility throughout the 5-year program. Responsibilities for design and vane testing were those of the Westinghouse Power Generation Systems Division (formerly Gas Turbine Division). All ceramic materials and components for testing and evaluation, with the exception of insulator parts, were supplied by the Norton Company under a government approved subcontract agreement with Westinghouse.

*ERDA Contract E(40-1)5210-KVD-10628-CE

1.4 COMPONENT DEVELOPMENT

1.4.1 STATOR VANE DEVELOPMENT

Figure 1-7 shows a block diagram flow chart of the major factors in the stator vane development as they actually occurred over the 5-year program, beginning July 1, 1971 and ending June 30, 1976. The major factors are vane design and analysis, fabrication, NDE, testing and failure analysis. The chart is shown in graphic form such that each factor can be easily traced horizontally with time and the interaction of different factors can be traced vertically. The general flow of the program is from top left to bottom right, leading to the final 2500°F static rig test demonstration. Feedback loops as they occurred are included to help illustrate the complexity of this comprehensive development program. Major decision points in time are indicated by an asterisk (*), and where applicable, the effect of that decision, e.g., to discontinue an activity, is indicated by an X. Major milestones are circled. Numbers 1, 2, and 3 refer to first, second and third generation vane designs.

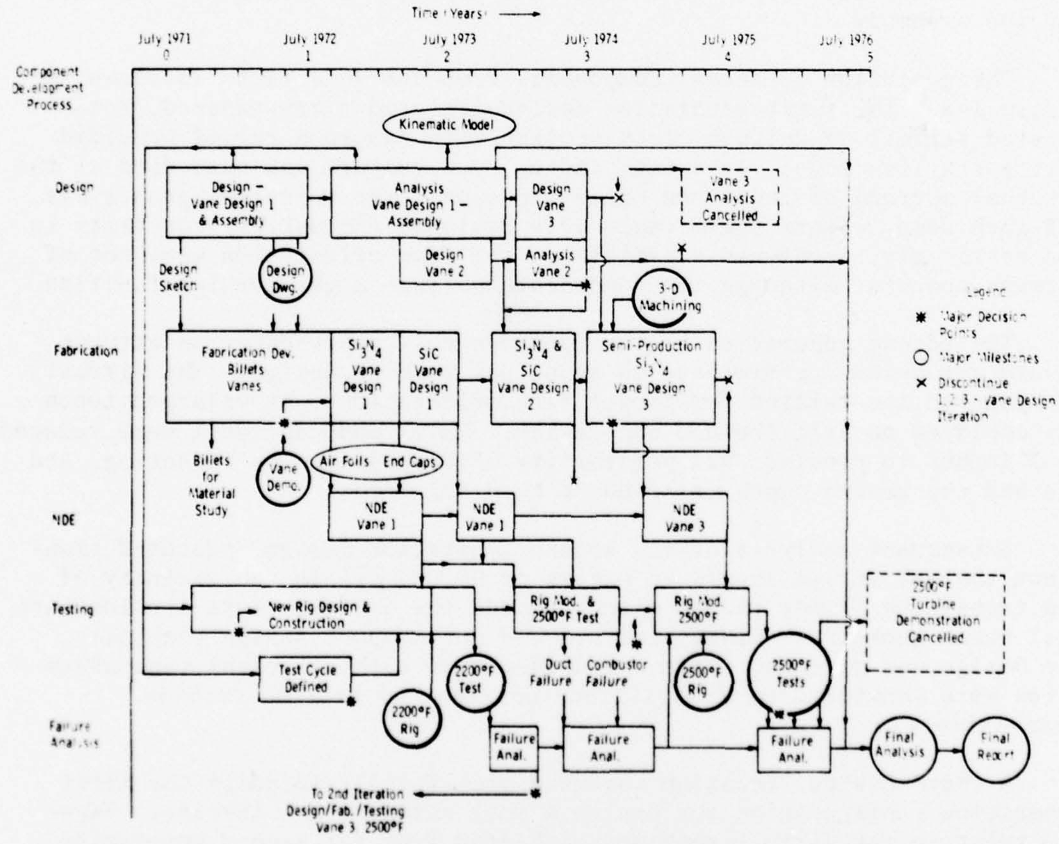

Figure 1-7. Stator Vane Development on Stationary Turbine Project

1.4.1.1 Design and Analysis

Preliminary design studies and two-dimensional finite element and difference analyses produced conceptual versions of a novel three-piece ceramic stator vane design consisting of an airfoil and two end caps for final reduction to practice and test. Within the constraints of fixed chord to pitch ratios, an airfoil cross section one-half that of a production type (Westinghouse 251, gas turbine) air-cooled, superalloy, first-stage stator vane was adopted as a practical and realistic means to keep transient thermal stresses within an envelope of physical properties of hot-pressed silicon nitride and silicon carbide. Under worst anticipated operating conditions of an emergency (fuel trip) shutdown, a maximum, principal, out-of-plane tensile stress of 41,000 psi, occurring at the leading edge was calculated for the airfoil section using essentially unsubstantiated property data from the literature. End cap dimensions reflected an incremental portion of the inlet circumference of the W 251 machine (nominally 5-1/2 ft diameter) with length determined as the design distance between the transition piece and the first rotor stage. A circumferential array of eighty assemblies, i.e., eighty airfoil sections with one-hundred-sixty end caps was required for the full turbine assembly.

The evolution of actual components from design efforts is shown in Figure 1-8. The first generation design featured a non-tapered, non-twisted airfoil of uniform cross section with generous relief provided at the trailing edge. An 8-inch radius of curvature was specified at the external surface of inner and outer end caps. The torroidal groove was 1/2 inch deep. Since these vanes were designed exclusively for tests in the static rig, aerodynamic efficiency and flow orientation were not of primary concern, although the components perform a gas turning function.

The second generation stator vane assembly represented an attempt toward aerodynamic efficiency in an actual turbine design. The airfoil was tapered and twisted for proper flow orientation. An enlarged tenon was employed to fill the end cap cavity. Major end cap radii were reduced to 3 inches to preclude all possibility of disposition by racheting, and the end cap groove depth was reduced to 0.375 inch.

Subsequent analysis of the second generation design indicated transient thermal stress levels in excess of 90,000 psi in the vicinity of the transition fillet radius which blended the airfoil cross section into full tenon geometry. Since analysis did not support design viability, the design was given no further consideration although eight vane assemblies were manufactured from silicon nitride and silicon carbide respectively.

A third design iteration was made specifically to adapt the first generation configuration for use in a full rotating gas turbine. Taper and twist in the airfoil remained unchanged from the second generation

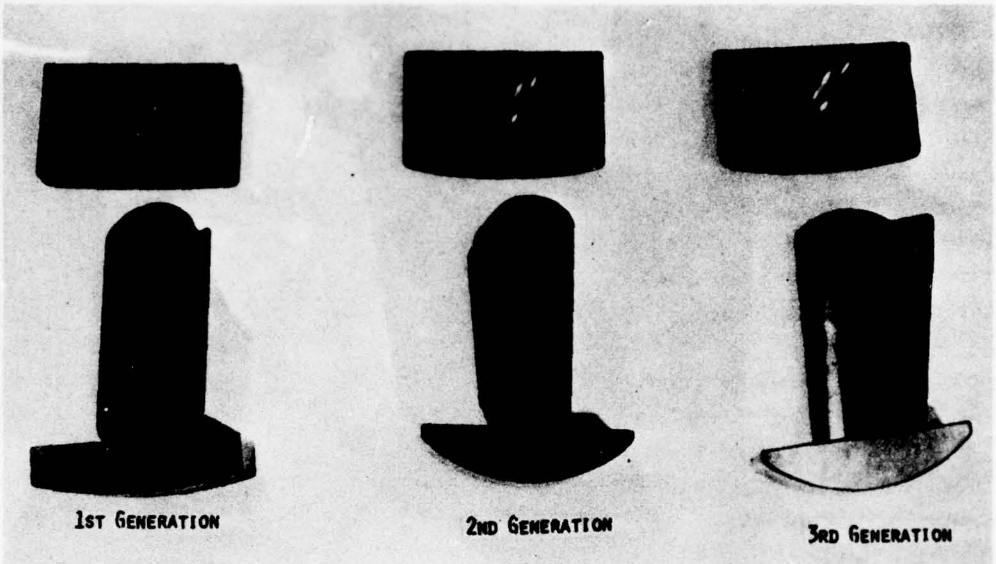

Figure 1-8. Stator Vane Design Iterations

1. Parallel Sided Airfoil
2. Tapered-Twisted Airfoil with Full Cavity Filling Tenons
3. Tapered-Twisted Airfoil

specification. End cap geometry was essentially the same as that of second generation assemblies. Although the third generation stator vane assembly was designed for the test turbine demonstration, a cascade of eight, with replacements, was tested in the static rig at a peak temperature of 2500°F to complete the program. A detailed postmortum 3-D finite element analysis of this vane could not be justified within DARPA funding limitations, September, 1974 (Figure 1-7).

The replacement of air-cooled, superalloy vanes (Figure 1-9) with ceramic vane assemblies for higher temperature service required the redesign of the entire first turbine stage. A spring-loaded, multi-component, sandwich structure was employed between the inner and outer support ring segments as illustrated in Figure 1-10. The exploded view of Figure 1-11 shows a silicon nitride airfoil between inner and outer end caps. Lithium aluminum silicate (LAS) insulators and metal shoes are also shown. A spring and plunger arrangement was used to apply the bundling force at the outer support ring location. The insulators and shoes were sized to bridge two stator vane assemblies so that, in effect, the radially inward-directed spring loads reacted in series combination across parallel pairs

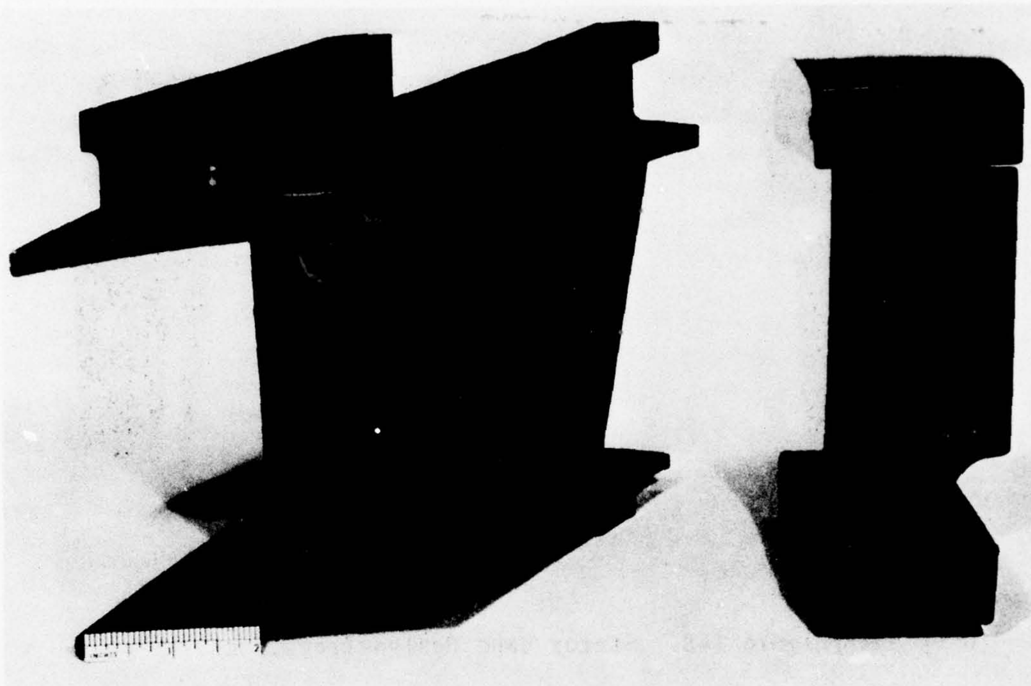

Figure 1-9. Comparison of Integral Superalloy Vane with Simply Supported Three-Piece Silicon Nitride Vane

of end caps and airfoils. A full-scale kinematic model of the vane assembly was constructed and used to prove out the mechanical integrity of the vane assembly concept.

1.4.1.2 Stator Vane Fabrication

With the exception of a hollow vane development program at Energy Research Corporation, in which attempts were made to produce a silicon carbide airfoil section by chemical vapor deposition (CVD), all materials, i.e., hot pressed silicon nitride and silicon carbide, and stator vane components for test and demonstration were manufactured either by or through the Norton Company. Within 9 months of the program start, Norton demonstrated the feasibility of producing the vane airfoils and end caps by diamond grinding methods.

From an initial group of forty HS130 silicon nitride billets, twenty prototype vane assemblies were fabricated to the first-generation design specification by diamond grinding methods. Ten billets were selected randomly from the original forty for engineering property characterization.

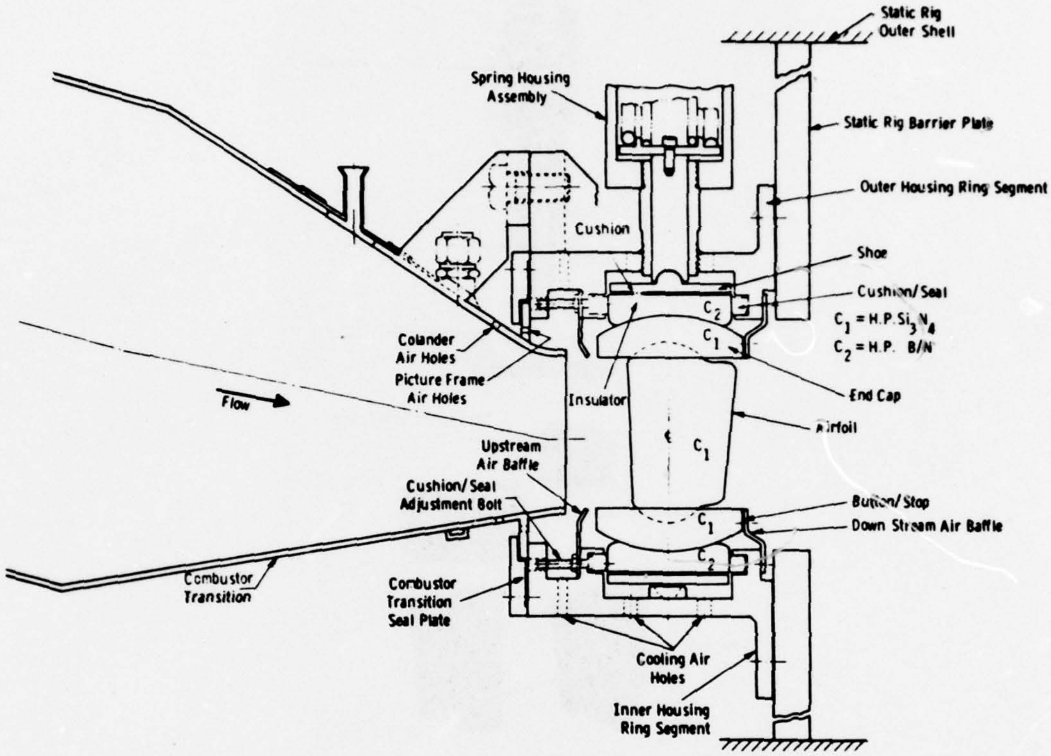

Figure 1-10. Longitudinal View of the Ceramic Vane with Support Structure - 2500°F Static Rig Test

Norton delivered eight additional first-generation vanes made from Noralide NC203 silicon carbide. Sixteen stator vane assemblies (second generation design), i.e., eight each, were produced from Noralide NC132 (improved HS130) silicon nitride and Noralide NC203 silicon carbide, respectively.

Having developed good experience with fabricating ceramic vanes from hot-pressed Si_3N_4 and SiC, a semi-production machining process was initiated for the manufacture of 100 vane assemblies for turbine testing. The airfoil processing is illustrated in Figure 1-12.

The starting point was hot-pressed 3 x 6 inch billets contoured to the pressure side airfoil radius. Triangular slabs were removed from the suction side to generate an angular airfoil preform with reference surface tabs. These preforms were then shipped to Ex Cello (Connecticut), a company well experienced in the manufacture of compressor blading. They previously isolated two machines in their shop for airfoil machining:

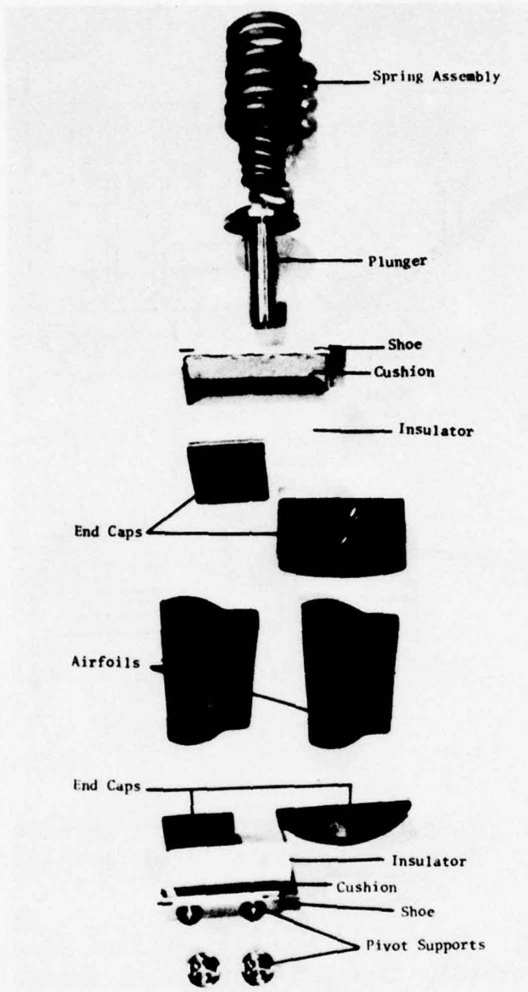

Figure 1-11. Exploded View of Three-Piece Vane Assembly and Associated Mounting Parts

one machine was equipped with a 100 grit resin-bonded diamond wheel for rough grinding and the other with a 320 grit wheel for finish grinding. Ex Cello formed the airfoil in a two-step operation using a "drum cam following" grinder. After inspection, Norton removed the end reference tabs, and rough cuts were made to form an angular presentation of the tenon at both ends of the airfoil. Ex Cello then performed the tenon grinding operation through the use of precision metal shuttle fixtures and contoured grinding wheels. After inspection the airfoils were finished at Norton. A special guillotine gauge was built to verify the

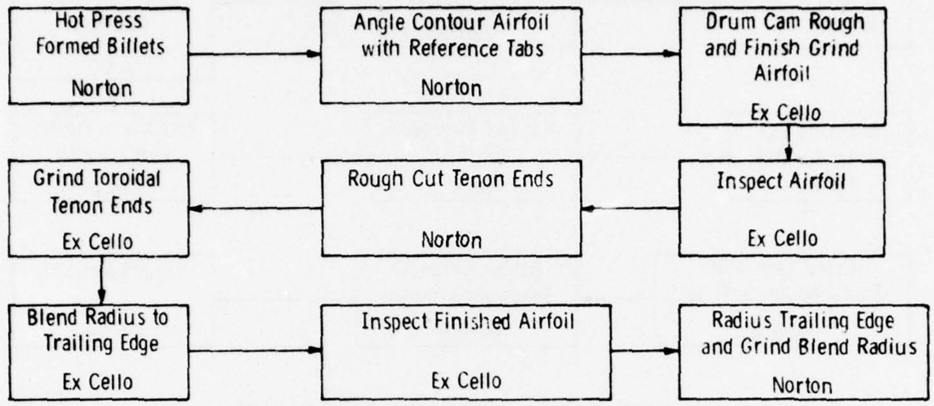

Figure 1-12. Airfoil Processing

airfoil cross section at prescribed section locations. An optical comparator and 5X mylar were used to inspect the major and minor radii which collectively projected the tenon geometry.

The end cap processing was done at Norton and one of its machining vendors. Figure 1-13 shows the end cap processing procedure. Using fixtured parts and contoured wheels, a gang grinding process was attempted. Rectangular hot-pressed billets were gang pressed. The cavity was formed by plunge grinding. Compound curvatures on the major end cap surface were diamond ground before final finish grinding of the edges and corners.

These improved manufacturing techniques not only resulted in high quality parts, but reduced cost to one-third that of the original prototypes.

An order for 100 Si_3N_4 stator vanes manufactured by the above methods was terminated with the decision (Figure 1-7) not to proceed to turbine testing. However, for static rig testing 28 airfoils and 42 end caps were manufactured. All parts were inspected by NDE methods prior to testing. Compared to the earlier HS130 material, the NC132 Si_3N_4 was reasonably free of material defects. This showed the progress that Norton Company had made in refining their powder processing methods. No serious internal defects were disclosed and airfoil finishes were within design tolerances. The as-ground airfoil tenon finish was 8 rms and the major surfaces were 12 rms.

1.4.1.3 Non-Destructive Evaluation (NDE)

All billet materials and stator vane assembly components were certified with respect to minimum room temperature flexural strength (average

END CAP PROCESSING

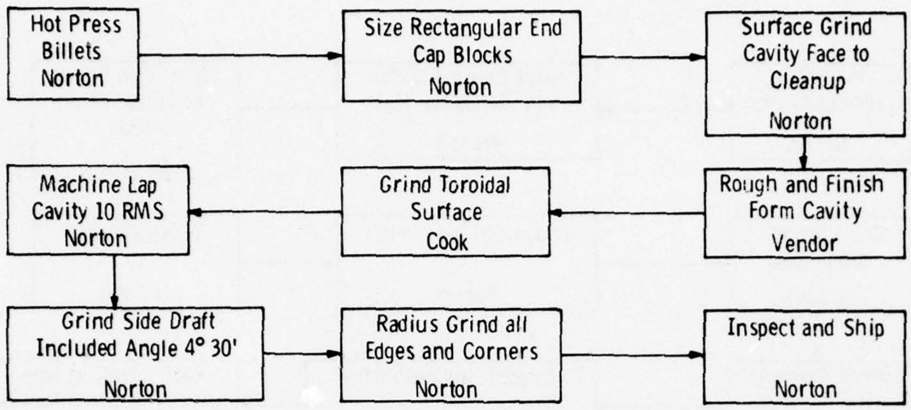

Figure 1-13. End Cap Processing

minus 2 standard deviations >90 ksi) and density (>3.18) by the Norton Company. Surface conditions and internal defects were qualified by Westinghouse using fluorescent dye penetrant, X-ray radiography and ultrasonic scanning. Voids, striations and high and low density inclusions greater than 100 microns were identifiable by methods perfected as part of the program.

1.4.1.4 Static Rig Development

In January 1972 plans (Figure 1-7) to design and build a highly instrumented static rig for testing the ceramic vane assembly were implemented. A cascade of eight ceramic vanes between two confining metal side vanes, representing an 1/8 segment of a full turbine row, was assembled for test (Figure 1-14). The rig (Figure 1-15) was modified several times in the course of testing. The first version was equipped with a standard production-type W251 combustor, metal exhaust duct and metal mixer for Phase I (September 1973) tests of the first-generation design, HS130 silicon nitride stator vanes with LAS insulators at 2200°F.

The combustor, a silicon carbide exhaust duct, and ceramic mixer were damaged severely during the Phase II (October 1974) testing of first-generation silicon nitride (HS130) and silicon carbide (NC203) stator vane assemblies after five cycles of operation at 2500°F.

The final version of the rig was modified to ensure reliable operation at 2500°F (Figure 1-16). Modifications included the use of a highly film-cooled Haynes 188 combustor, water-cooled metal exhaust duct and spray water-cooled mixer. The rig was made ready for Phase III (October 1975) testing of third generation NC132 silicon nitride vanes and boron nitride (Carborundum Combat M) insulators at 2500°F.

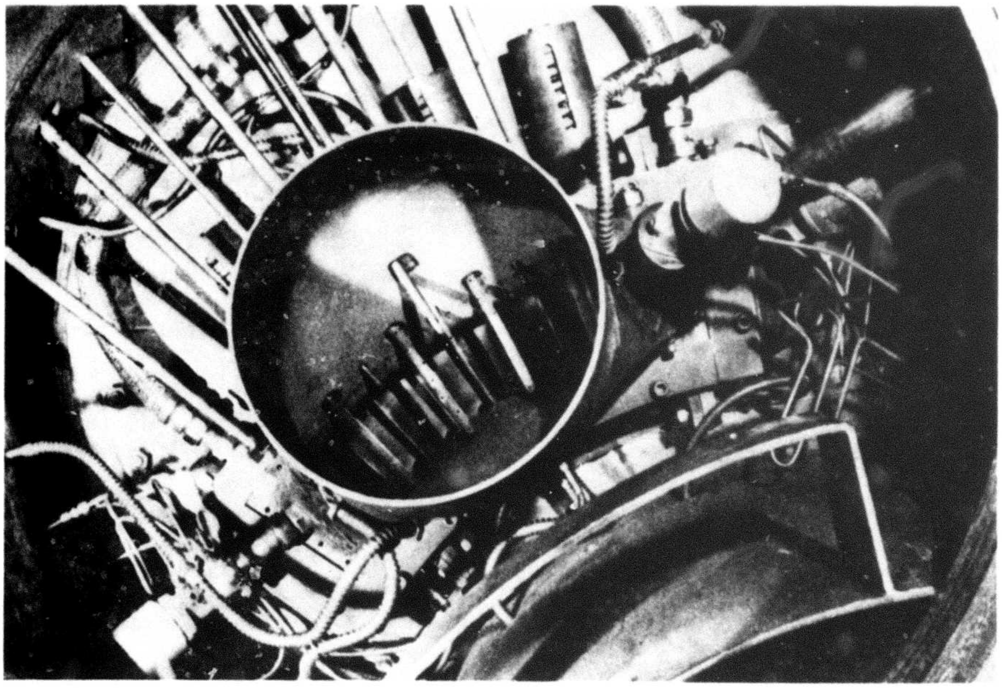

Figure 1-14. Fully Instrumented Vane Assembly

The test plan was to subject the ceramic vane assemblies to 2200°F first and then 2500°F. Since significant thermal stresses in a vane result from startup and shutdown cycling, 100 thermal transient cycles were chosen for the test objective. The cycle was considered more severe than typical utility turbine operation, yet maintained stresses at moderate levels in the ceramic vanes. The cycle (Figure 1-17) consisted of a cold start to idle. a 10°F/sec ramp to peak temperature (2200°F or 2500°F) representing full load, a hold for 3 to 5 minutes to collect steady-state data, and then a shutdown to simulate either a controlled emergency shutdown condition that frequently occurs in practice or a fuel trip out that infrequently occurs in normal service. The controlled emergency shutdown transient (Static Rig Test Sequence) from full load is described for comparison with typical turbine operation as follows:

Controlled Emergency Shutdown (Static Rig Test Sequence)	Typical Turbine Operation (Normal Shutdown Mode)
Full load → 2000°F, immediate	Full load, → 1040°F linear at 9°F/sec
Hold 45 sec at 2000°F	Hold 120 sec at 1040°F
2000°F → 1200°F at 25°F/sec	Shut off fuel supply
Shut off fuel supply	Total time ∿ 240 seconds
Total time ∿ 120 seconds	

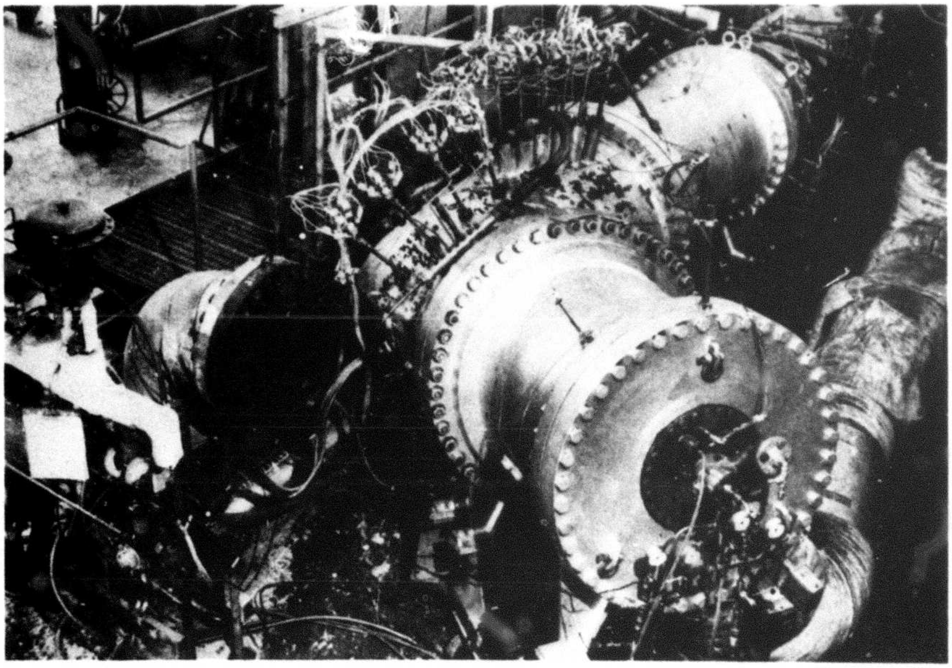

Figure 1-15. The Static Rig for Testing Ceramic Stator Vanes at 2200 and 2500°F (Mitered Section Is 42 Inches in Diameter)

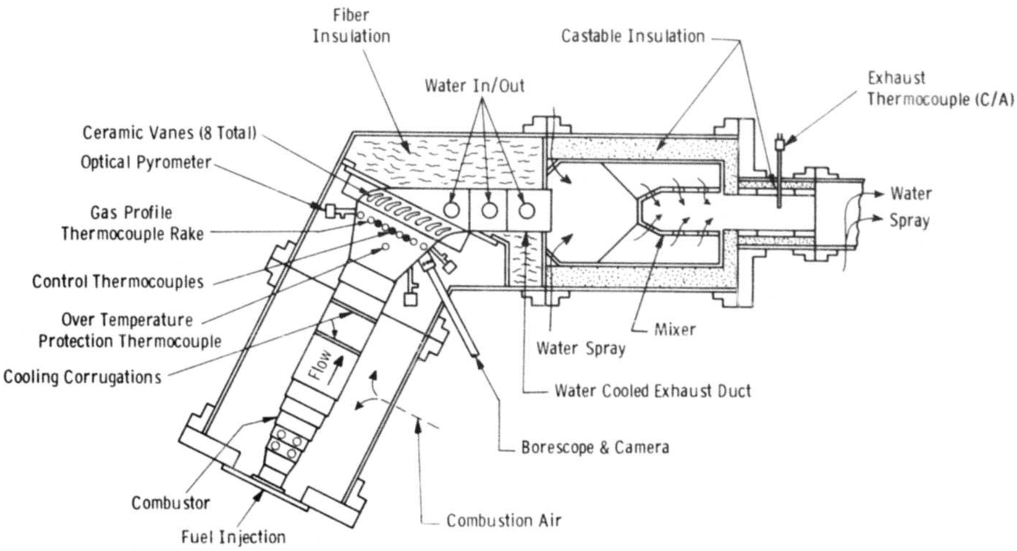

Figure 1-16. Plan View of 2500°F Static Test Rig

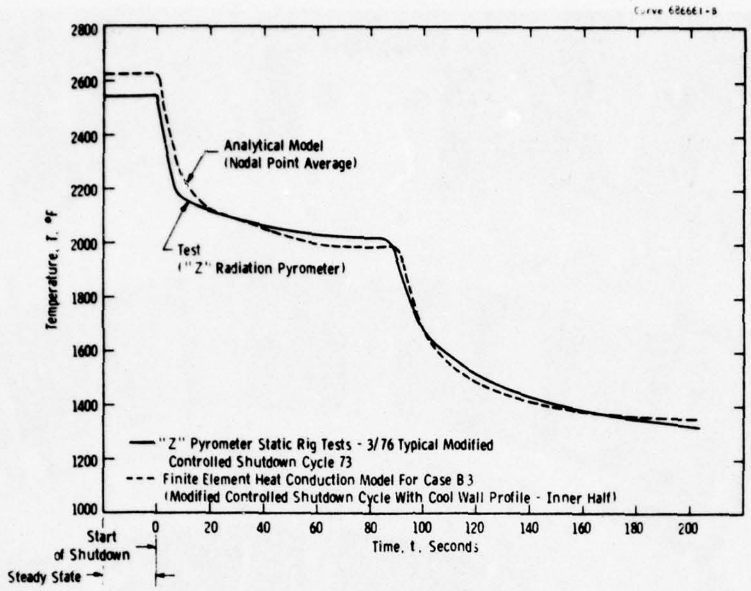

Figure 1-17. Typical Cycle for 2500°F Static Rig Test-Controlled Shutdown Condition

The fuel trip condition or emergency shutdown as now practiced is a near instantaneous ramp from full load (peak temperatures) to temperatures equivalent of idle in 12-15 seconds. This infrequent case represents the most severe condition that ceramic vanes would be expected to encounter in service(possibly three times in the normal life of a machine). Such a situation would cause ceramic vane failure according to analysis.

It should be noted that the vanes were not subjected to a normal turbine shutdown programmed for linear ramp down from full load at ~1°F/sec which takes about 1020 seconds.

1.4.1.5 Static Rig Testing

In September 1973 nine cycles were run at 30 percent turbine simulation, sixty-three at 50 percent simulation and the final thirty-two at 80 percent simulation (8 atmospheres pressure compared to 10.5 characteristic of a W251 turbine), for a total of 106 cycles at 2200°F. Vanes were exposed approximately 9 hours at the peak temperature. The stator vane assembly components remained functional at the end of testing (Figure 1-18). Failure analysis revealed that four of the eight silicon nitride airfoils (Figure 1-19) and two of sixteen end caps were damaged.

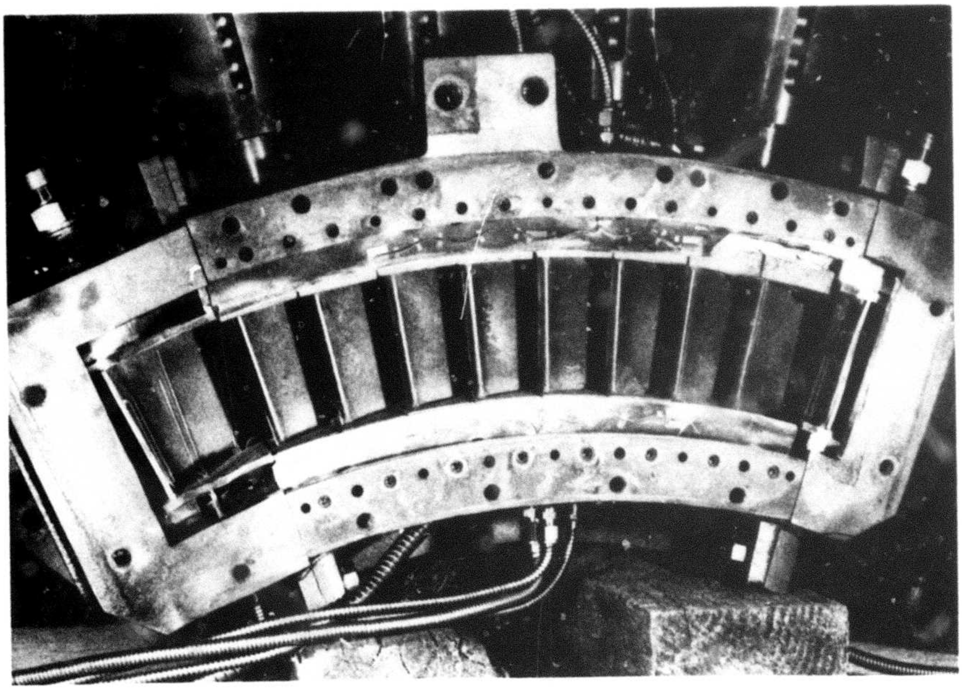

Figure 1-18. Stator Vane Test Fixture with Three-Piece Si_3N_4 Stator Vanes and LAS Insulators at the Completion of 2200°F Static Rig Tests (106 Cycles)

These failures were found to be induced by an abnormal edge loading condition at the airfoil/end cap junction that resulted from out-of-tolerance machining. All LAS insulators failed by chipping or cracking that was induced by temperature instability of the material. Since all silicon nitride vanes that met the design specifications performed very successfully and since the machining problem was easily corrected, the decision (Figure 1-7) was made to proceed with 2500°F test plans and to explore the feasibility of using boron nitride rather than LAS insulators.

Phase II testing (October 1974) of both silicon nitride and silicon carbide vane assemblies at 2500°F lasted five cycles. The test was interrupted due to a creep rupture failure (implosion) of the production-type Hastelloy X, hot wall combustor used. This accidental occurrence caused a temperature excursion to 3000°F and fuel trip under choked flow conditions. Cracks were observed in the silicon carbide airfoils prior to the incident, indicating its inferior thermal shock resistance compared to silicon nitride. The condition of the vane assembly components after the combustor failure is shown in Figure 1-20 where silicon nitride vanes in positions 1-4 on the left side of the cascade

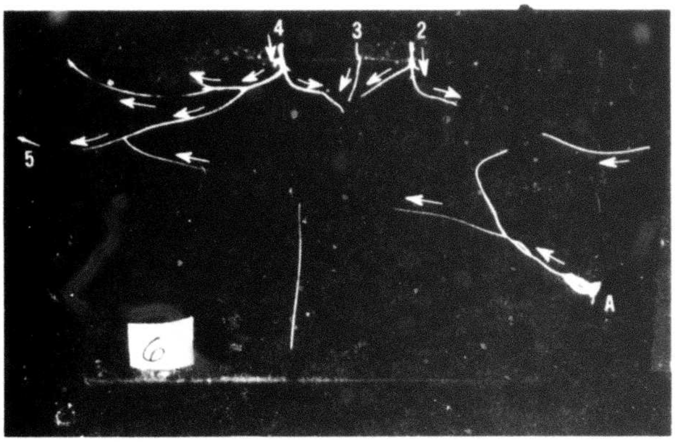

Figure 1-19. Airfoil 6 from 2200°F Static Rig Tests

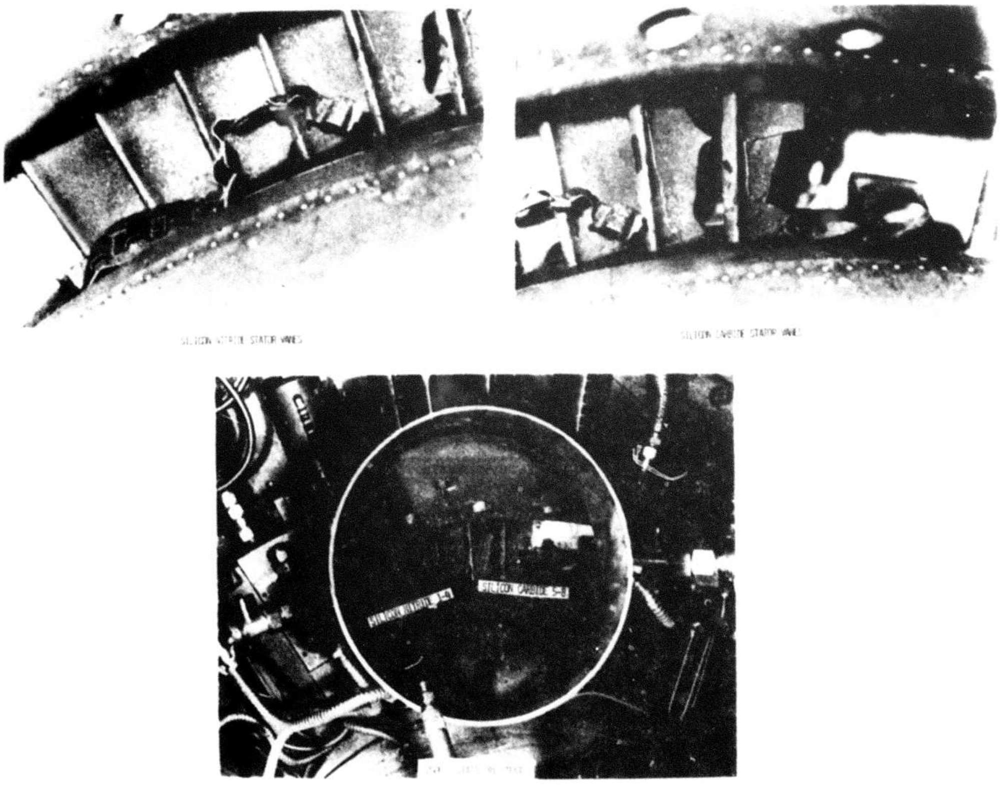

Figure 1-20. Static Rig Test Results After Five Cycles at 2500°F - Catastrophic Rig Failure

survived, while the four silicon carbide vanes in positions 5-8 failed catastrophically. Failure analysis revealed that silicon nitride airfoil 1, inner end cap 2 and outer end cap 4 contained cracks. All SiC components salvaged from the tests showed cracking due to thermal stress. Hot pressed silicon nitride and boron nitride insulators survived the test without damage. LAS insulators in both the original and redesigned geometry failed catastrophically. Both LAS and SiC materials were dropped from future test plans (Figure 1-7).

Testing at 2500°F resumed in October 1975 after modification of the static rig to prevent rig failures. The gas temperature profile resulting from the cool-wall combustor showed peak-to-average temperatures much larger than those of previous tests. Preliminary runs showed that when the eight-vane cascade (third-generation silicon nitride vanes and boron nitride insulators) was at the steady-state condition, vanes 3, 4 and 5 operated at the peak loading temperature of 2500°F+; vanes 2, 6 and 7 at 2200°F; and vanes 1 and 8 below 2200°F. Moreover, all vanes experienced large radial gradients. Attempts were made to rectify this situation, but analysis showed that combustor development, not within the program scope, was required.

The program plan for final test demonstration at 2500°F called for one hundred transient controlled shutdown cycles similar to those run at 2200°F. Provisions were made to inspect the test assembly after increments of 25-30 cycles were completed. Three test series were actually conducted as follows:

A. 1-25 cycles, October 1975

B. 26-60 cycles, December 1975

C. 61-103 cycles, March 1976

An assembly error, causing displacement of the upper end caps resulted in several edge loading and chipping failures in the first 25 cycles (Figure 1-21). Airfoils 5, 6, 7, and 8 were affected. Also, a thermally induced crack was observed in the vane 3 airfoil which was one of two airfoils (the other at position 6) purposely preoxidized prior to testing for 100 hours at 2500°F. This failure provided the result expected from laboratory studies that NC132 Si_3N_4 airfoils are degraded in strength by high temperature static oxidation.

Cycles 26-60 were run with all damaged parts replaced (Figure 1-7). During these next 35 cycles, borescope observations showed that airfoils 5 and 6 developed cracks at their leading and trailing edges after 23 and 30 cycles, respectively (Figure 1-22). Both failures were attributed to thermal stress. The failure of airfoil 6 was again anticipated due to the preoxidation treatment. All other components survived.

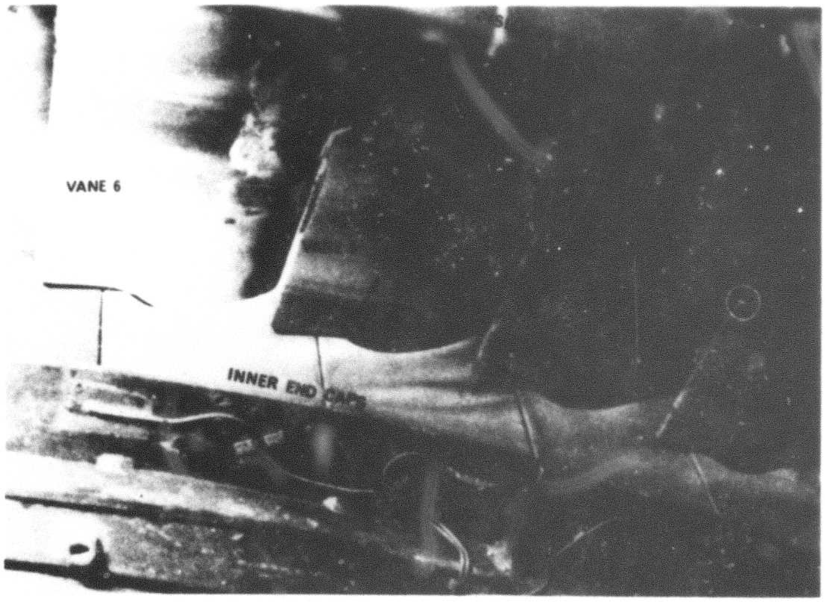

Figure 1-21. Failure Indications in Silicon Nitride Stator Vane Components After 25 Cycles of Transient Testing in the Static Rig at 2500°F

The final 43 cycles were run after replacing (Figure 1-7) the two failed airfoils 5 and 6 from previous cycles and the remaining preoxidized airfoil 3 that survived the previous cycles. Testing was completed without incident (Figure 1-23). None of the airfoils, end caps or insulator components developed any visual cracks during the test and none could be detected immediately following disassembly (Figure 1-24). Failure analysis later revealed a single trailing edge crack in airfoil 8. This failure apparently resulted from the extraneous thermal effects of an air-cooled metal side vane located in very close proximity to airfoil 8.

1.4.1.6 Analysis of 2500°F Static Rig Test

A detailed 3-D finite element stress analysis was performed to determine the important component of the maximum principal stress (σ_{mp}) and its magnitude and location for a vane subjected to specified thermal loads. These maximum principal stresses were used for comparison with material strength data from room temperature to 2300°F, using as a basis an elastic-to-failure criterion in order to explain component performance. Above 2300°F, NC132 Si_3N_4 exhibits inelastic behavior so that a pseudo-elastic-to-fracture stress was estimated.

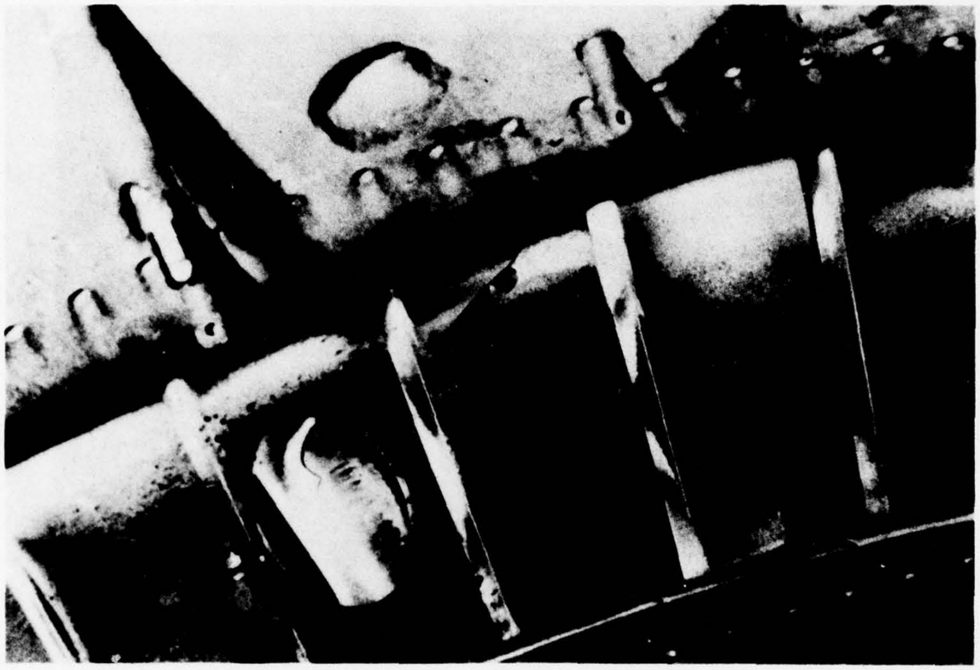

Figure 1-22. Failure Indications in Silicon Nitride Stator Vane Airfoils (Cycles 26-60) During Static Rig Testing at 2500°F

The boundary conditions chosen for the stress analysis were those of the static rig operating under steady-state and transient conditions from a peak temperature of 2670°F*. Vane airfoil 4, which was the centrally positioned vane in the hot zone of the static rig, was the principal airfoil used for the stress analysis. It was monitored during testing with radiation pyrometers at three locations.

The several cases run to obtain the desired information were as follows:

- Steady-state operating mode at peak temperature
- Transient operating mode from peak temperature

---

*2670°F represents an interpolation of the true hot spot temperature from extrapolated temperature profiles at 2500°F. The rig is monitored and controlled at 2500°F by a radiation pyrometer sighted on the expected hot spot location which may not coincide exactly with the true hot spot location.

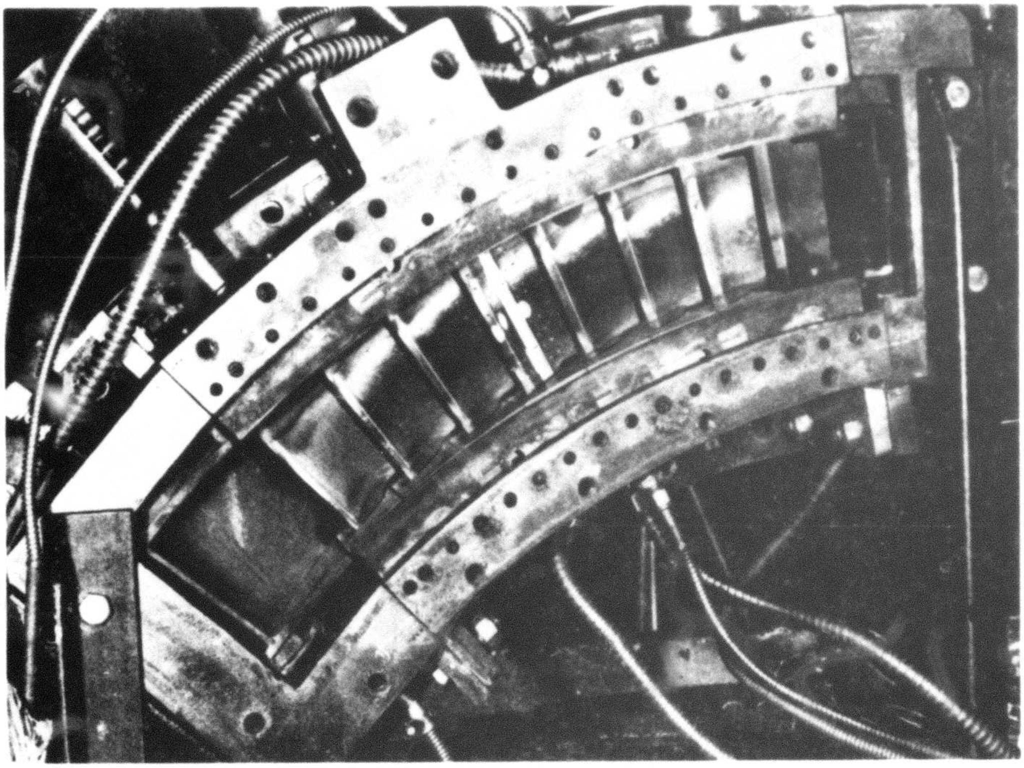

Figure 1-23. Stator Vane Test Assembly (Cycles 61-103) After Static Rig Testing at 2500°F

A. Linear controlled emergency shutdown, 25°F/sec

B. Nonlinear controlled shutdown, typical of actual test

- Instant fuel cutback from 2500°F to mid-load at 2000F.
- Controlled shutdown from mid-load to idle at 25°F/sec.

C. Fuel trip out - instantaneous shutdown.

- Temperature profile source and type

1. Idealized combustor - uniform temperature.
2. Production-type hot wall combustor - moderate temperature gradient profile.
3. Experimental cool wall combustor - steep temperature gradient profile.

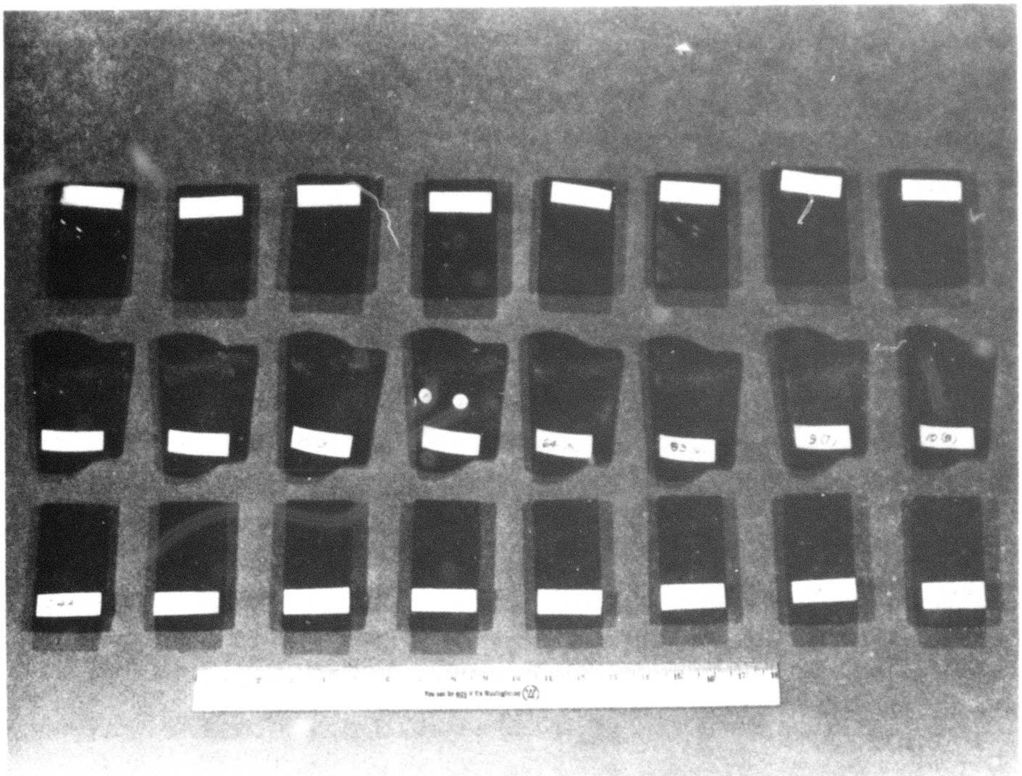

Figure 1-24. Vanes Disassembled After Cycles 61-103 of Static Rig Testing at 2500°F

It should be noted that most of the 2500°F static rig transient tests are represented by the Case B3.

The analysis showed the following significant results for the present and future tests:

1. The significant component of the maximum principal stress (σ_{mp}) that develops in the ceramic vanes due to thermal loading is the out-of-plane radial (σ_z) stress.

2. The shape of the radial direction gas temperature profile on a vane is more important than overall temperature in controlling the maximum principal stress.

3. The effect of a large radial-direction gas temperature profile at steady state is to raise σ_{mp} and alter its location from leading

to trailing edge of the vane airfoil. Similarly, during a given transient, the large radial profile increases σ_{mp} early in the cycle and alters its location from leading to trailing edge of the vane airfoil. An example of results is shown in Table 1-2 where the effects of three different temperature profiles are compared for the transient mode of nonlinear controlled shutdown. As may be seen, the cool wall combustor case produces the highest stress. Needless to say, a production hot-wall type combustor capable of producing 2500°F+ gas should be developed in order to maintain moderate stress levels in first row ceramic vanes.

4. A statistical analysis of NC132 Si_3N_4 tensile properties showed that the relatively large standard deviation, σ_{SD} ($\sim\pm10$ kpsi, R.T. to 1400°F) would result in some failures for the various transient shutdown cases analyzed.

5. A performance analysis based upon a safety margin of -2σ (2 x standard deviation from average strength) for the conditions shown in Table 1-2 concluded that case B1 would result in $\sim$11 percent probability of failure, case B2 up to 20 percent probability of failure, and case B3 up to 80 percent probability of failure.

TABLE 1-2

AIRFOIL TRANSIENT THERMAL STRESS FOR NONLINEAR CONTROLLED SHUTDOWN FROM 2500°F

			Maximum Principal Stress		
Case	Description	Time (sec)	Plane Height and Location*	σ_{mp} (psi)	T (°F)
B1	Uniform	0	50% L.E.-S	0	2650
B1	Uniform	8	50% L.E.-S	23,327	2250
B2	Hot Wall	0	50% L.E.-S	14,000	2660
B2	Hot Wall	8	50% L.E.-S	27,203	2290
B2	Hot Wall	98	50% L.E.-S	33,050	1830
B3	Cool Wall	0	50% T.E.-S	27,000	2640
B3	Cool Wall	4	50% T.E.-S	52,707	2360
		8	50% T.E.-S	48,900	2130
		94	50% T.E.-S	41,987	1800

*L.E. -S = leading edge suction side; T.E.-S = trailing edge suction side.

**Interpolated local hot spot temperature from extrapolated temperature profiles resulting from radiation pyrometer controlled temperature at control area location (2500°F).

6. Under the rare occasion of instant fuel trip using the cool wall combustor profile, the maximum principal airfoil stresses over localized areas can reach values as high as 72,000 psi at 1650°F in 20 seconds. These are sufficiently high to cause a very high probability of failure.

In summary, 103 cycles of static rig testing were completed as a final evaluation of silicon nitride stator vane performance at 2500°F+ peak temperature conditions, representing 0.8 turbine simulation. Three of eight airfoils (1, 2 and 4) survived all of the test conditions (mechanical and thermal) without failure. Four airfoil failures were attributed to thermal stresses, and of these two were preoxidized to have lower than nominal material strength. All insulators and end caps performed well as did the metal support structure. When the results of stress analysis were compared with the 1975-1976 test results, good agreement was obtained regarding the location (mid-height), position (leading or trailing edge) and direction of stress (radial) that produced failures. A comparison of calculated maximum principal stress with statistical tensile strength of NC132 Si_3N_4 revealed that the strength variability of this material was sufficient to cause the observed thermal failures. The test results and analysis concludes that by using an improved combustor and materials with reduced varaibility in properties, a practical turbine shutdown cycle can be developed in the future which would result in an extremely low probability of failure.

1.4.2 CERAMIC ROTOR BLADE DEVELOPMENT

Root attachment, where high contact loads occur as a result of the centrifugal forces of rotation, appears to represent the major problem to be solved in the development of a ceramic rotor blade. An analysis of the the distribution of these stresses in three-dimensional geometry as a function of variable geometric design parameters, material parameters and time temprature conditions of turbine operation is not possible with conventional 2-D analytical methods. Three dimensional capability had to be developed.

The foremost accomplishment of the rotor blade development task was the partial development and refinement of "WISEC," Westinghouse Isoparametric Element Code, which makes use of isoparametric of 3-D "brick" elements for stress analysis of complex structures (Figure 1-25). These are a relatively new development and are capable of accurately representing curved boundaries which can be programmed with relative ease. In order to meet the requirement of ceramic rotor blade analysis, the features developed and implemented into the computer code were as follows:

1. A family of 3-D mixed isoparametric elements.

2. The ability to handle a variety of loading conditions for both stress analysis and heat conduction elements.

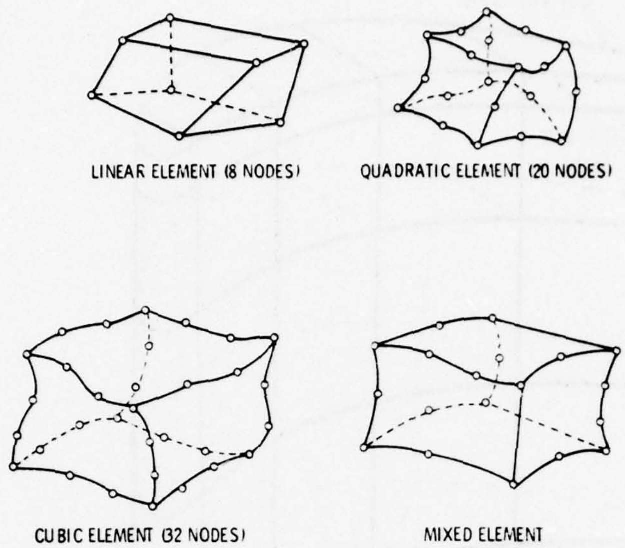

Figure 1-25. Family of Isoparametric 3-D Elements

3. The ability to accommodate temperature-dependent material properties.

4. The ability to model isotropic or anisotropic material properties.

The ceramic rotor blade development task was terminated (Figure 1-7) in 1974 when program efforts were redirected solely toward vane development. Thus, a final rotor blade design and planned computer simulation of performance were not achieved. Good progress was made, however, in demonstrating the applicability of WISEC to rotor blade design evaluation by designing and analyzing a blade concept from prior art. This blade which featured a dovetail root attachment was sized to the Westinghouse W251, 30 MW turbine in keeping with the development procedure adopted for ceramic components. The root cross-sectional geometry was first optimized analytically by conducting a parametric, two-dimensional finite element analysis. Properties for hot-pressed Si_3N_4 were used, and the blade root was subjected analytically to the centrifugal force field resulting from the 4850 rpm rotational speed of the W251 turbine.

Having selected a preferred root design, it was analyzed in detail using WISEC to determine the magnitude and location of stresses and temperatures. The analysis was conducted for 4850 rpm rotational speed and steady-state temperature conditions. Figure 1-26 illustrates the 3-D model used for analysis where vertical and horizontal section members represent sections analyzed. The important result of this work was the capability to determine the magnitude and distribution of stresses and temperatures in a complex ceramic blade.

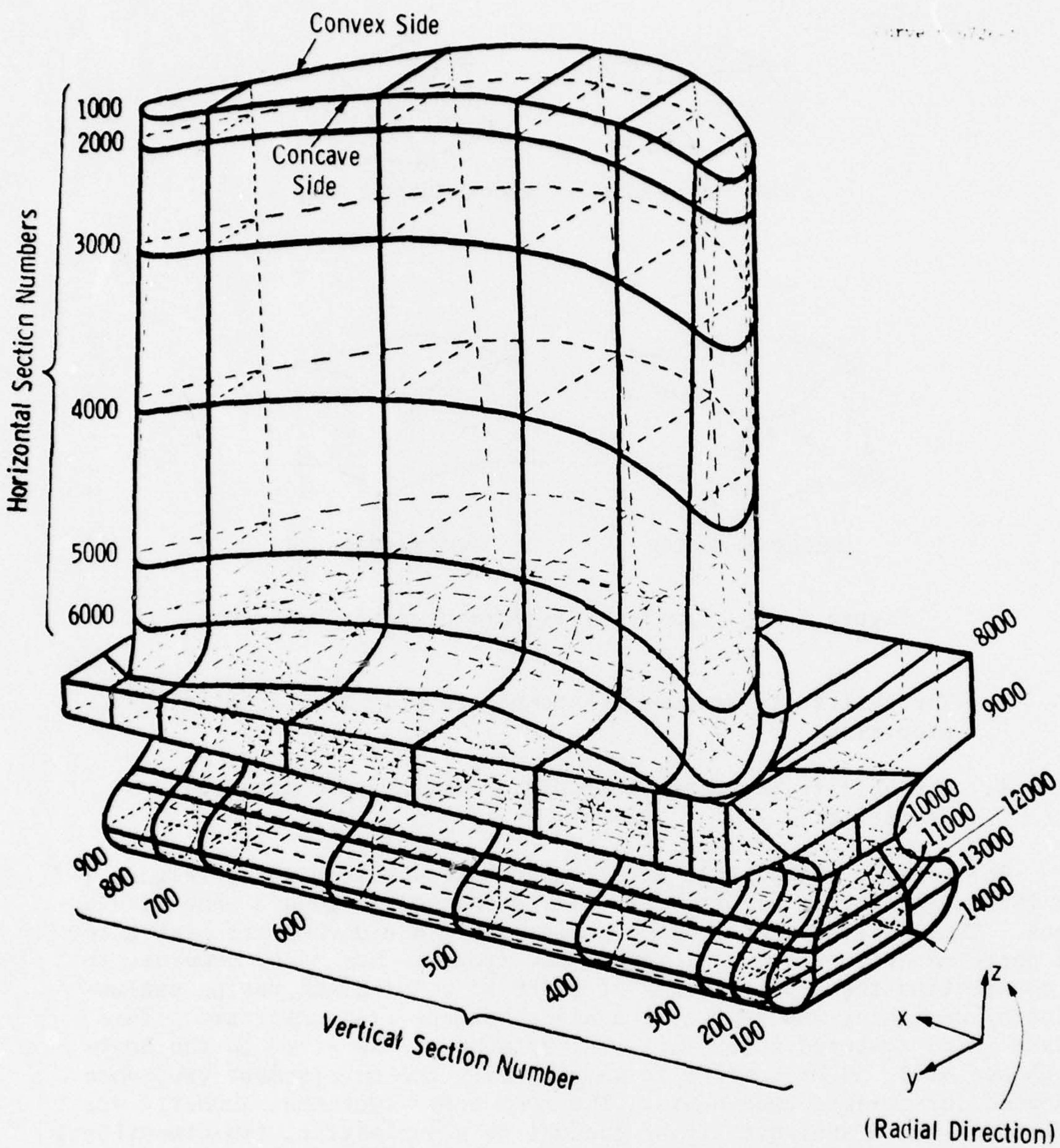

Figure 1-26. Computer Plot of Ceramic Rotor Blade

Based on this work, a ceramic rotor blade development program was initiated with the Electric Power Research Institute in April 1975 under Contract RP 421-1.(17-20)

1.5 MATERIALS TECHNOLOGY

Materials technology formed the basis for component development and, as described in the program plan (Section 1.3.2), this activity was conducted throughout the program in parallel with design, fabrication, NDE, testing and failure analysis efforts. There were three major subtasks conducted under Materials Technology: Materials Engineering Data, Materails Science and Nondestructive Evaluation. This work concentrated solely on the materials selected for stator vane development, namely, hot-pressed Si_3N_4 and SiC vanes, Owens-Illinois LAS and Carborundum BN insulators. A materials technology task was also undertaken by Ford Motor Company who concentrated mainly on reaction bonded Si_3N_4 and SiC, but who also required hot-pressed material for rotor hubs. Excellent interaction occurred between Westinghouse and Ford on materials problems and exchange of materials information.[1-9, 21-23]

1.5.1 MATERIALS ENGINEERING DATA

As shown earlier in Figure 1-6, the physical, thermal and elastic properties of the candidate materials were measured extensively in order to make the computer codes for stress analysis complete. In addition, failure properties that relate to component reliability were determined. These include strength, creep, fatigue, friction, and wear together with oxidation and hot corrosion/erosion effects on strength. Insofar as possible, the proeprty determinations were based on a statistical test plan.

It is not the express purpose of this summary to provide extensive property data because these will be given in Volume IV, "Materials Technology" of the final report. Specific accomplishments will be highlighted with problem areas properly identified. Representative properties for hot-pressed Si_3N_4 which clearly affected static rig test results at 2500°F are appropriate, however, as discussed in the following paragraphs.

Test methods and equipment were developed for the mechanical property testing of structural ceramics in air at temperatures up to 2600°F. Test modes included tension, compression, tensile and compressive creep, low and high cycle fatigue, torsional shear and flexure. Specific developments were as follows:

1. A technique for aligning tension and compression specimens for uniaxial testing.

2. An extensometer and strain measuring technique for testing to 2500°F in air.

3. Compressive creep apparatus for testing in air to 2500°F.

4. Torsion test equipment and a method for measuring shear strength and shear modulus to 2500°F in air.

5. Ceramic tensile specimen grips and load train ports.

6. Tension-to-compression flexural fatigue fixture for low-cycle fatigue tests to 2500°F in air.

7. High temperature extensometer to measure creep strain in air.

8. A compressive loaded ceramic fixture for strength or creep testing at high temperatures in air.

The early observations of anisotropic properties in hot pressed silicon nitride for "strong" and "weak" directions were identified with the material stressed normal and parallel to the hot pressing direction, repspectively. This anisotropy was attributed primarily to density variations with crystallographic orientations contributing approximately 15 percent as measured in the hot pressed billet. Since the maximum principal stress in an operating ceramic vane develops during thermal transients as an out-of-plane σ_z stress which is coincident with the strong direction of the material, anisotropy was not considered to be a detrimental design factor.

Thermal and elastic properties, i.e., conductivity, specific heat, expansion, modulus of elasticity and Poisson's ratio, were determined from room temperature to 2500°F for hot pressed Si_3N_4, Norton HS130 (noralide NC132) and hot pressed SiC, Norton NC203. Figure 1-27 shows representative properties of Si_3N_4 used for the stress analysis of vanes tested at 2500°F in the static rig.

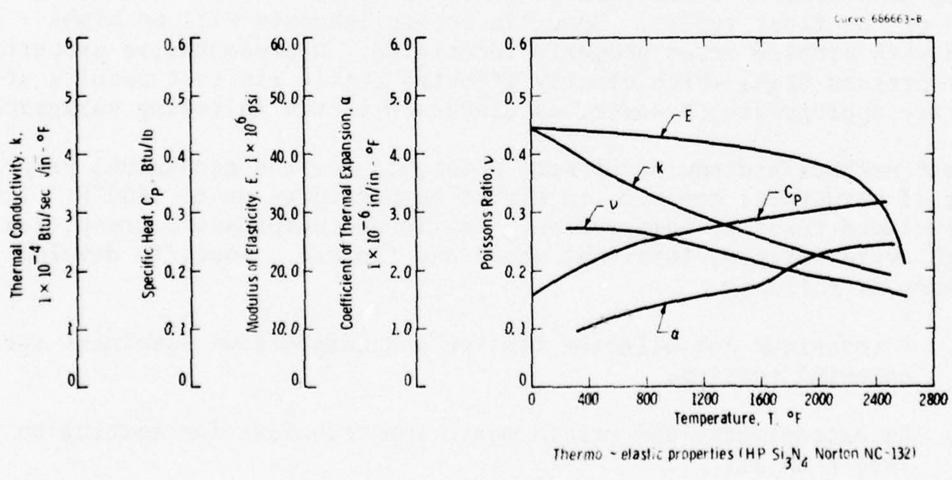

Figure 1-27. Thermo-Elastic Properties (HP Si_3N_4-Norton NC132)

Tensile specimens (Figure 1-28) were employed to measure ultimate strength, elastic-modulus, creep and stress rupture from room temperature to 2500°F for both HS130 Si_3N_4 and NC203 SiC. Figure 1-29 illustrates the tensile strength behavior of hot pressed Si_3N_4 as a function of temperature.

Flexural tests were used extensively to measure strength, high, and low cycle fatigue from room temperature to 2500°F for both HS130 Si_3N_4 and NC203 SiC. Figure 1-30 illustrates the flexural strength of hot pressed Si_3N_4 in the strong direction for selected strain rates. The average flexual strength closely approximated two times the average tensile strength from room temperature to 2500°F. In Figure 1-31, the flexural strength is averaged over a large number of billets. These data are consistent with Figure 1-30. The major problems identified with the strength of hot-pressed Si_3N_4 were a) the variability and b) the continued decrease from room temperature upward to higher temperatures, particularly the rapid decrease above 2200°F. This behavior resulted directly from processing defects and impurities, respectively.

Weibull analysis was introduced into the program to correlate flexural and tensile properties, but more importantly to determine the relative effects of volume and surface defects. Analysis showed that from room temperature to 1800°F, surface defects dominated strength while at 2300°F and above where inelastic deformation occurred, both surface and volume defects controlled strength.

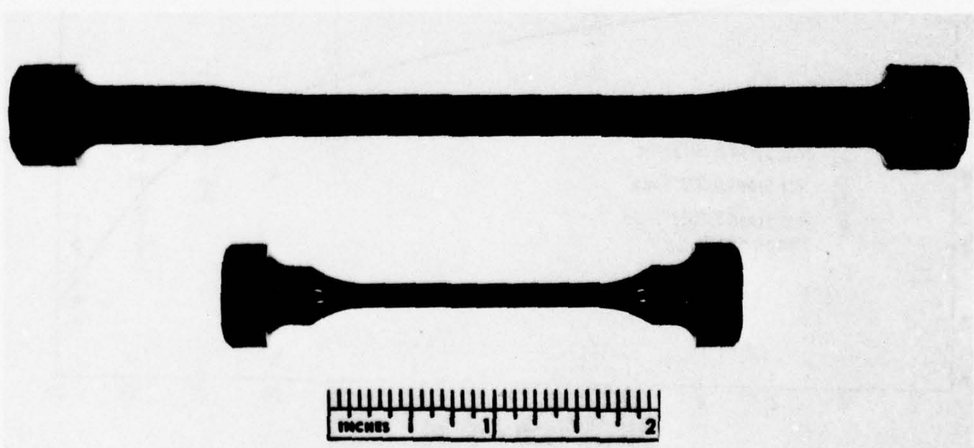

Figure 1-28. Tensile Specimens

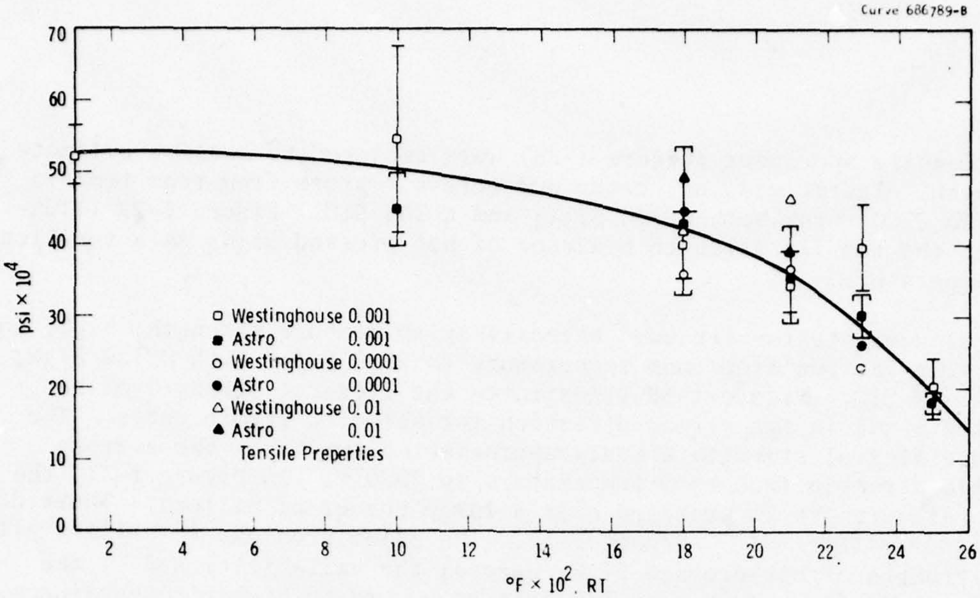

Figure 1-29. Tensile Properties of Norton HS130 (NC132) Silicon Nitride

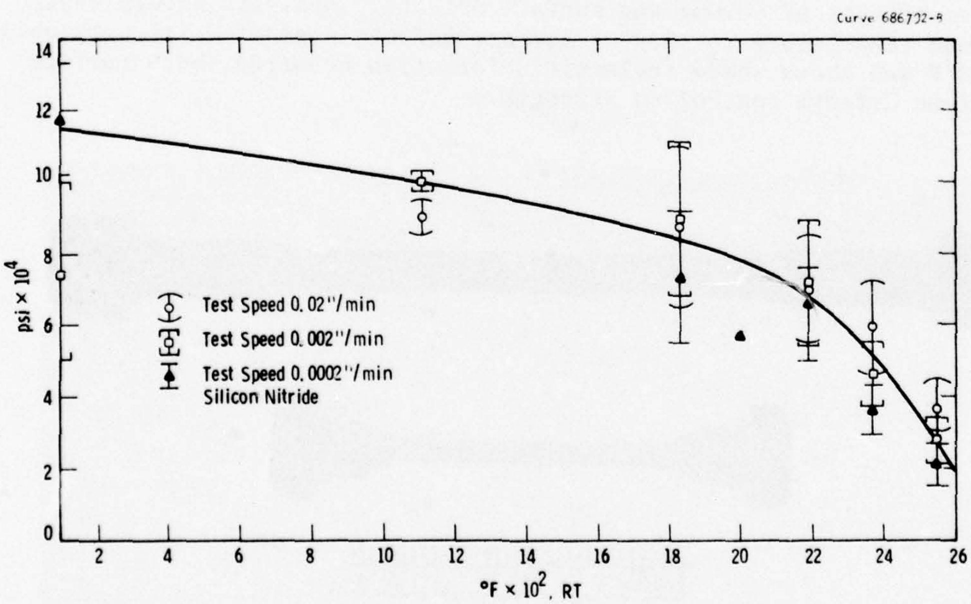

Figure 1-30. Flexural Strength of Norton HS130 (NC132) Silicon Nitride (Strong Direction)

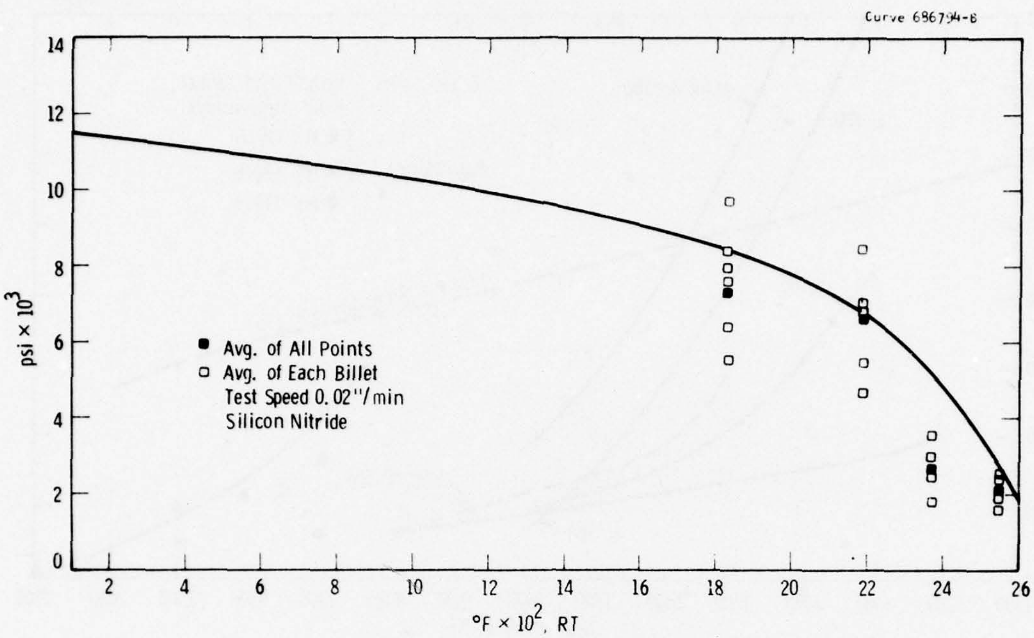

Figure 1-31. Billet Variations in Average Flexural Strength of Norton HS130 (NC132) Silicon Nitride

Stress-strain data in the tensile mode showed that HS130 and NC132 Si_3N_4 were essentially elastic to failure up to 2300°F at loading rates in the range of 0.001 in/in/minute. Inelastic deformation was found at temperatures above 2300°F.

Creep and stress rupture properties of HS130 Si_3N_4 and NC203 SiC were determined from 1800 to 2500°F. Figure 1-32 seems to indicate superior stress rupture properties for HS130 Si_3N_4 as compared to superalloys between 2000 and 2200°F. Its properties are poor at 2500°F, however. The creep resistance of this material appears satisfactory for vanes operating up to 2200°F because the steady-state stresses are low (<5,000 psi). A 10,000-hour stress rupture life was determined for NC132 Si_3N_4 at 2100°F under 10,000 psi stress.

Environmental effects on HS130 Si_3N_4 and NC203 SiC were measured. These included hot corrosion/erosion in pressurized test passages at 2000°F and 2500°F for periods up to 250 hours using fuel contaminated with Na, S and V. Results showed that both commercial materials exhibited excellent hot corrosion/erosion resistance at 2000°F (Figure 1-33), and fair resistance to 2500°F (Figure 1-34). Flexural strength measurements showed that 2000°F exposure resulted in no strength degradation, whereas 2500°F exposure resulted in strength reduction of up to 25 percent for 500 ft/sec gas flow at 3 atmospheres pressure.

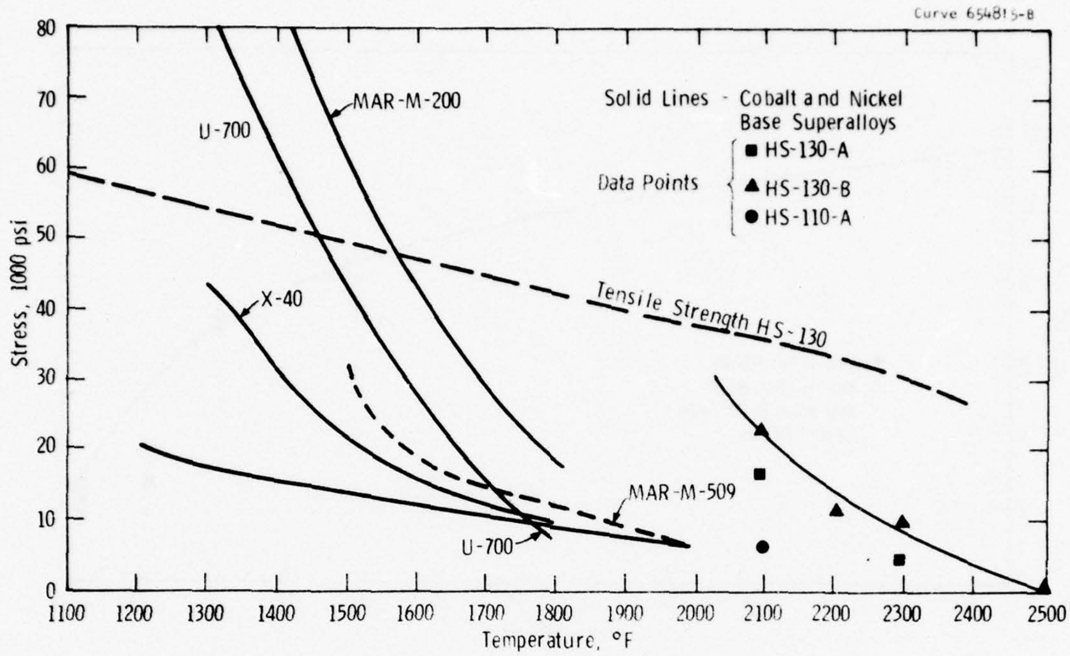

Figure 1-32. The 1000-Hour Stress-Rupture Characteristics of Si_3N_4 and Selected Superalloys

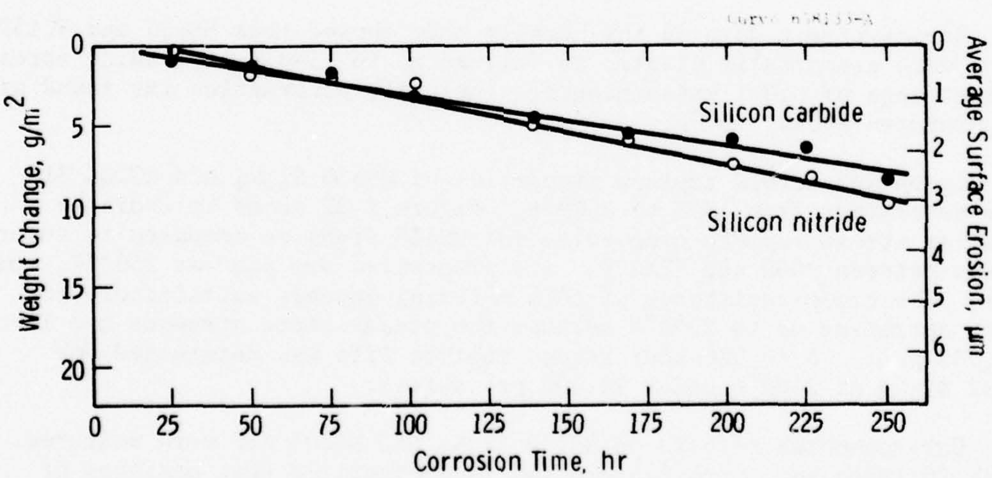

Figure 1-33. Corrosion-Erosion Behavior of Hot Pressed Silicon Nitride and Silicon Carbide in Turbine Passage at 2000°F, 3 atm and 500 ft/sec

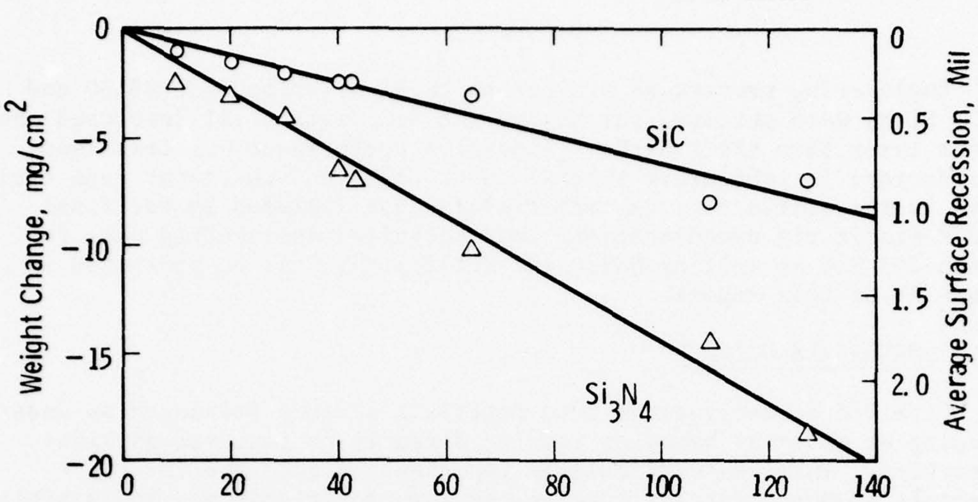

Figure 1-34. Corrosion-Erosion Behavior of Silicon Nitride and Silicon Carbide in Turbine Passage Test at 2500°F, 3 atm at 500 ft/sec

Extensive oxidation studies revealed that the strength reductions in hot-pressed Si_3N_4 and SiC were due to bulk impurities that migrate to the surface and react with the protective SiO_2 layer to form complex silicates, which in turn react with the underlying substrate material. The end result is the formation of sub-surface pits and cavities that act as flaws to reduce strength. This serious problem was overcome by modifications in composition which will be described in the Materials Science Summary.

Friction, wear and fretting measurements were made for materials used in the stator vane assembly. These included Si_3N_4 versus Si_3N_4, Si_3N_4 versus LAS, and Si_3N_4 versus several high temperature steels and alloys at room temperatures to 1600°F.

Insulator material candidates for the stator vane assemblies included Owens Illinois' LAS (Lithium Alumina Silicate) material and Carborundum's BN. These off-the-shelf materials were characterized to validate the suppliers data and to obtain specific information for design. Friction and wear, flexural strength, elastic modulus, shear modulus and thermal expansion were included.

Finally, experimental thermal shock studies were conducted early in the program to evaluate the candidate materials and to verify the computer programs used for stress analysis. These tests were performed on instrumented cylinders subjected to transient thermal conditions in a pressurized test passage.

Engineering properties similar to those described for HS130 and NC132 Si_3N_4 were obtained for Norton-203 SiC, a material developed about a year later than HS130 Si_3N_4. Since its performance was less than satisfactory in laboratory thermal shock tests and in stator vane cyclic tests in the static rig, the material was not included in the final 2500°F static rig demonstration. More detailed engineering data for Norton-203 SiC as well as HS130 and NC132 Si_3N_4 will be presented in Volume IV of this report.

1.5.2 MATERIALS SCIENCE

Detailed investigations into materials science developed an understanding of material behavior leading directly to improved physical properties. This was particularly important because the ceramic materials proposed for gas turbine use were relatively new and exhibited considerable capacity for improvement. The materials science investigations were defined by the engineering requirements of the system and related to the commercial materials employed as part of the stator vane development program. Contributions were made to fabrication process control, superior properties and extended life expectancies for selected ceramic materials. Results of this work were fed directly to the Norton Company for use in the refinement of HS130 and eventually for development of NC132 silicon nitride.

The microstructures of commercial grade hot-pressed Si_3N_4 (Norton HS110 and HS130) and hot-pressed SiC (Norton NC203) were characterized This activity encompassed an in-depth determination of primary and secondary phases, phase distribution, chemistry, impurities, major inclusions and other processing defects. Crystal structure defects were also identified. The microstructural characteristics and fractography were correlated with thermal, mechanical and physical properties.

A comprehensive theoretical and experimental study was made of the environmental stability of Si_3N_4 and SiC and the SiO_2 surface layer which is so necessary for these materials to operate successfully in an oxidizing environment at high temperatures. This work also provided the information needed to explain oxidation effects on strength as discussed under the Engineering Project Data Section. An important result of the Materials Science work at Westinghouse was the identification of potential problems with both Si_3N_4 and SiC, most of these being related to powder processing and impurities. In the case of hot-pressed Si_3N_4, foreign inclusions and impurities were found to influence performance significantly:

- The kinetics and mechanisms for creep and slow crack growth in hot-pressed Si_3N_4 were determined.
- Foreign inclusions as summarized in Figure 1-35 act as flaws, causing wide variations in mechanical properties and strength reductions as great as 50 percent.

- Detrimental impurities such as Ca, Na and K cause high temperature strength reductions and poor creep and oxidation resistance due to their role in forming low melting silicate phases at grain boundaries.
- Certain additives required to densify Si_3N_4, like MgO, are a problem in that they contribute to the formation of detrimental phases.

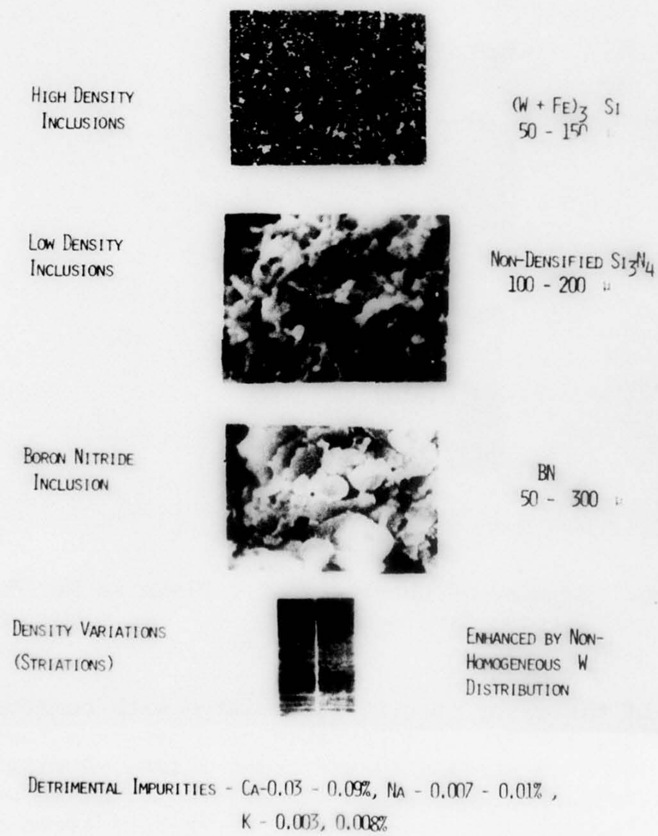

Figure 1-35. Summary of Characteristic Flaws in Hot-Pressed Silicon Nitride

In the case of fully dense hot-pressed SiC (Norton NC203), the major problems identified were relatively low fracture toughness and inferior thermal shock resistance. This means that this candidate is very

susceptible to surface damage and crack initiation by mechanical and thermal loads. Processing defects associated with NC203 SiC are summarized in Figure 1-36. These include second phases, crystal defects and inclusions.

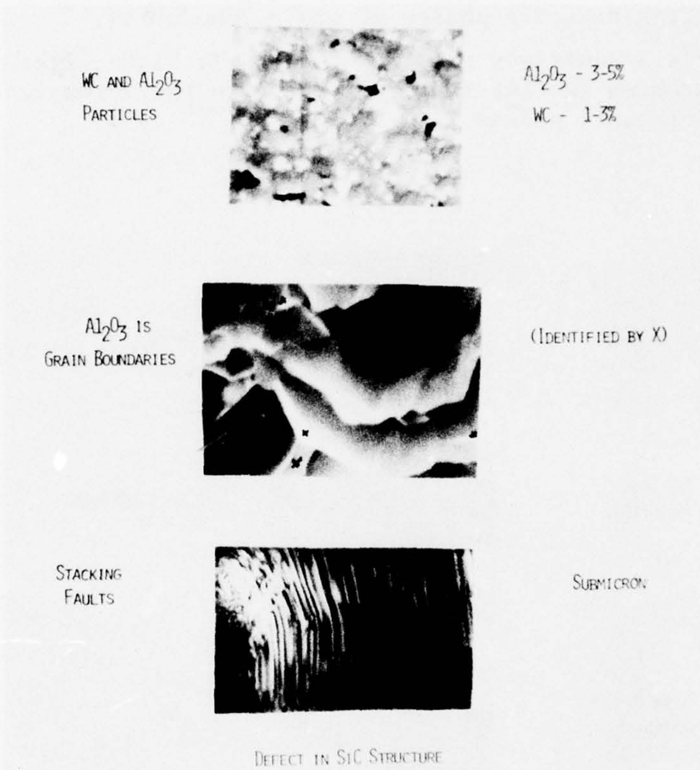

Figure 1-36. Summary of Characteristic Flaws in Hot-Pressed Silicon Carbide

Definition of the major problems associated with commercial grades of hot-pressed Si_3N_4 and SiC made possible good progress toward their solution with respect to processing and composition. During the program period, the high-temperature strength of hot-pressed Si_3N_4 was improved by 400 percent. Further progress was made to improve creep and oxidation resistance. Specific accomplishments were made in the development of improved materials. This resulted from Westinghouse in-house work and other DARPA* sponsored activities as follows:

- The development of a high purity, high α-phase Si_3N_4 powder.
- A systematic determination of the effect of major impurities such as Ca, Fe, Al, Na, and K on strength, creep and oxidation resistance of Si_3N_4

*DARPA order number 2697, contract number 01269.

- A systematic determination of the effect of hot pressing additives on the strength, creep and oxidation resistance of Si_3N_4 and SiC.
- A determination of the phase relationships in the Si_3N_4-MgO-SiO_2 system.
- The development of improved hot-pressed Si_3N_4 containing MgO and SiO_2. Figure 1-37 shows the improved creep resistance achieved in comparison to the industry standard, NC132 Si_3N_4.
- A determination of phase relationships in the Si_3N_4-Y_2O_3-SiO_2 system.
- The development of experimental Si_3N_4-Y_2O_3-SiO_2 materials showing excellent promise of high temperature strength, low creep and excellent resistance to oxidation to 2550°F. Figure 1-38 shows the relative oxidation resistance of $Si_3N_4 \cdot Y_2O_3 \cdot SiO_2$ compositions that have been developed. As shown, these new materials exhibit oxidation resistance comparable to that of chemically-vapor deposited Si_3N_4, i.e., intrinsic to that of pure Si_3N_4. These studies continue at Westinghouse under the sponsorship of the U. S. Energy Research and Development Administration (ERDA).[24]

1.5.2.1 Nondestructive Evaluation

Microstructural uniformity is considered essential for structural reliability in ceramics for gas turbine engine applications. The objectives of NDE were to identify and classify microstructural and macrostructural defects and to relate these to the component fabrication process. The ultimate goal was the definition of meaningful inspection methods and an acceptance criterion for components prior to installation in an engine. Procedures utilizing ultrasonics, X-ray radiography, dye penetrants and acoustic emission were applied to ceramic systems for evaluation purposes as follows:

- Suitability of dye penetrants for detecting surface-connected porosity and other surface defects was established for ceramic combustion turbine components.
- Sensitivity of commercial techniques in ultrasonic A&C scanning to low density inclusions and segregated voids in hot-pressed Si_3N_4 and SiC was established.
- X-ray radiography was used exclusively to identify high density inclusions greater than 150 microns and density striations in hot-pressed silicon nitride and silicon carbide billets, test specimens and components.
- Feasibility of applying acoustic emission to proof testing of ceramic components was determined.

Curve 690381-A

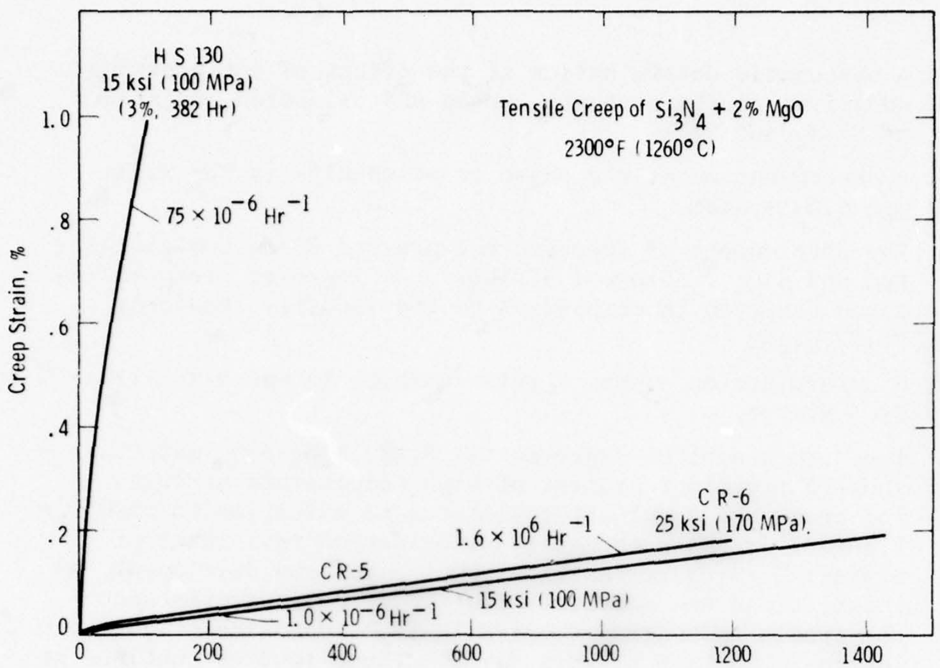

Figure 1-37. Tensile Creep of Silicon Nitride Hot-Pressed with MgO

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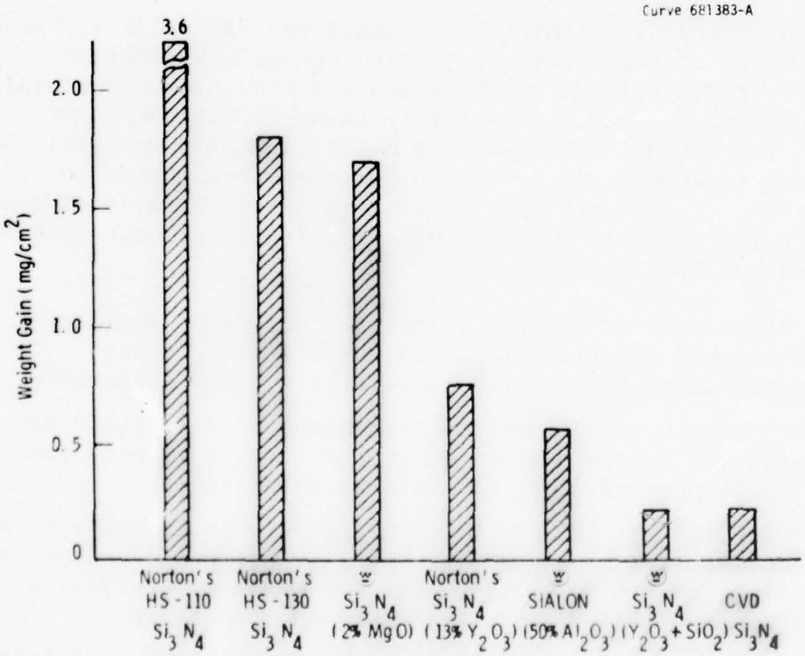

Figure 1-38. Comparative Weight Gains in Si_3N_4 after 400 Hours Oxidation at 2500°F in Air

1.6 THE ADVANCED TURBINE MODIFICATIONS

In order to accomplish the original planned objective of a 2500°F turbine test demonstration to validate the ceramic stator vane design, extensive modifications of the Westinghouse W251, 30 MW frame size test turbine were required. Specifically, modifications were necessary to accommodate the first-stage ceramic vane assembly and totally upgrade the machine for 2500°F operation. Design work progressed to where layout drawings for the turbine modifications were completed, and long lead-time items such as impingement-cooled first-row metal rotor blades were ordered. All of this activity was discontinued when the project objective was revised (Figure 1-7) to emphasize stator vane development and testing at 2500°F in the static rig. This revised objective was successfully met as described in Section 1.4.1.

SECTION 2

CONCLUSIONS

The successful use of ceramic components (combustors, stator vanes and rotor blades) in electric power generating combustion turbines can effect significant improvement in the overall efficiency of power conversion, providing an opportunity for higher operating temperatures and greater resistance to corrosion/erosion with a variety of fuels, while conserving fuel and other strategic materials. This incentive was known at the beginning of the program and has become increasingly important to U. S. energy problems. Nothing has occurred as a result of this program to indicate that ceramics cannot be developed to work in electric power generating gas turbines.

Other conclusions are as follows:

1. The DARPA concept of a system development approach, whereby efforts in ceramic design, materials, fabrication, testing and evaluation are drawn together and developed to establish the use of brittle materials in engineering applications, has proved to be a viable path to ceramic component development for industrial gas turbines.

2. The "ceramic design thinking" used to develop a three-piece first-stage ceramic turbine vane has proved vital to the demonstration of ceramic design feasibility. Design optimization must be achieved, however, to remove potential difficulties that could arise in practice, i.e., contact and edge loading damage.

3. The static rig test demonstration of ceramic vanes operating uncooled in a peaking duty mode of turbine operation from a 2500°F+ peak (hot-spot) temperature has encouraged the belief that ceramics can be applied to future gas turbines. However, intensive computer modeling and static rig testing are required to validate design concepts and materials capabilities.

4. As the property variability of "state of the art" ceramic candidates is reduced through improved processing methods and high temperature, and hot-wall combustors are developed, turbine operating cycles for the future should produce extremely low probabilities of ceramic component failure.

5. Major problems remain to be solved before ceramic components are proven useful for practical turbines. The foremost, of course, is the development and characterization of improved materials for extended life in high temperature operation. Present production materials and processes pose a serious problem to design engineers who must provide high reliability for a very conservative power generation business. Improved processing to reduce property variability, better NDE methods and procedures to detect life limiting critical flaws and their distribution, and probabilistic life prediction methodology to assess component reliability, over many thousands of operating hours, are examples of technological areas that must be addressed.

6. The production machining of ceramic hardware should not be ruled out as a practical means of manufacturing some components for electric power generating gas turbines. A semi-production process for billet pressing and airfoil fabrication by diamond grinding was demonstrated in this program. This resulted in a significant cost reduction. In the future, parts may be partially hot pressed or sintered to shape prior to final production machining of critical areas as a practical tradeoff to solve processing problems.

7. Good correlation between test results and stress analysis of ceramic components can be achieved when the test boundary conditions (heat transfer, temperature gradients, etc.) and material properties are well defined.

8. The maximum principal stress-failure criteria, as used in the present work to explain vane failures, provide a useful first approximation. However, a probabilistic treatment of lifetime prediction using fracture mechanics and statistical relationships must be developed to evaluate component performance accurately.

9. The engineering property data base for candidate ceramics should be expanded to include a determination of long-term tensile creep strain, stress rupture and low cycle fatigue. Environmental testing should contain an assessment of the effects of oxidation, hot corrosion and erosion on physical, mechanical and failure properties.

10. The properties of commercial hot-pressed Si_3N_4 and SiC as defined in this program are not adequate for long-term use in turbine vanes or blades above about 2200°F (hot-spot temperature). However, materials under development show promise of significant improvement, particularly in high temperature strength, creep and oxidation resistance.

11. Both Si_3N_4 and SiC show superior corrosion/erosion resistance at temperatures to 2000°F where turbine fuel contaminants can be most damaging due to condensation and reaction. The ability of these materials to maintain their strength after this exposure is most encouraging.

12. Detrimental oxidation of hot pressed Si_3N_4 above 2000°F can be prevented through composition control. An example is the use of Y_2O_3 + SiO_2 sintering aids to replace MgO in the production process.

13. While existing NDE methods and procedures have been refined and successfully used to inspect ceramic parts before and after testing, further refinement of X-ray radiography and high frequency ultrasonic scanning are required to detect small flaws and small flaw distribution. These must be developed.

14. Finally, the stationary turbine project is considered a successful demonstration of design innovation for brittle materials. Careful analysis and materials work have laid a solid foundation for future development. An important product of the program is a clear understanding of the key problems with directions indicated for their solution.

SECTION 3

RECOMMENDATIONS FOR LARGE TURBINE DEVELOPMENT

A comprehensive long-range national program should be started with the goal of attaining commercial status for a combined cycle power generation system incorporating ceramic gas turbine components capable of operating with coal derived fuels. Realistic turbine operating temperature goals should be established while defining an initial base-line engine design of which the technology program can be focused. A turbine inlet temperature goal of 2500°F appears reasonable because it permits the full use of technology developed over the past 6 years. If successful turbine engine performance is to approach an optimum, materials and fabrication development programs will be required and should be given high priority.

It is imperative that the technology development program be planned with performance review points and milestones so that recognition of an insurmountable obstacle would lead to immediate redirection to solve the specific problem.

The following are recommended to represent a Phase 1, 5 to 6 year intensive materials and design effort:

1. Base-Line Engine Definition to define explicitly the performance objectives of an advanced turbine engine containing ceramic components in order to set specific design goals and materials requirements.

2. Materials and Fabrication Development to a) improve the properties and reliability of gas turbine ceramics through accelerated materials and processing research aimed not only at improving current ceramics, but also providing basic information for the development of new materials, e.g., composites, coatings, etc., and b) to translate experimental materials from the laboratory to commercial facilities where sufficient quantities of consistent-quality material can be developed and produced for evaluation of engineering properties and component testing. It is strongly recommended that the comprehensive materials program be well organized and managed in a way that each participant is held responsible for specific developments that are dictated by the base-line engine requirements.

3. <u>Materials Characterization</u> to support the analytical design efforts by providing reliable engineering properties for stress analysis, evaluation of component structural integrity, and lifetime prediction. Failure property characterization, which represents a serious technological gap, should be conducted under combined loading conditions that are representative of planned rig and engine test conditions. This task is difficult and will require careful planning of critical experiments in order to be cost effective.

4. <u>Analytical Development</u> to provide the analytical tools needed for accurate evaluation of structural integrity, stress analysis and lifetime prediction. Very careful design and analysis will continue to be a requirement of large turbine design programs because expensive testing prohibits a "make and break approach." Computer modeling has already proved valuable to design evaluation and interpretation of test results. The computer codes, however, must be expanded and refined to handle a number of problem areas pertinent to ceramic design and evaluation.

5. <u>Failure and Life Prediction</u> to develop the methodology and techniques to make reliable lifetime predictions for ceramic components with and without proof testing. This is perhaps the most uncertain area of brittle material design and analysis because material response under combined loading conditions is not well understood and constitutive equations, e.g., describing material response to combined static and dynamic fatigue, have not been derived and probably will not be for some time. Present efforts to develop probabilistic treatments of time to failure in the presence of slow crack growth for simple loading conditions should be continued to verify the methodology. However, as combined load test data become available, the probabilistic treatment should be refined to obtain absolute failure and lifetime predictions.

6. <u>Component Development</u> to improve design methods and to develop and refine component designs. The required components are vanes, blades and combustors.

7. <u>Component Test Verification</u> to complete a loop in the design cycle prior to actual turbine testing. Laboratory rig testing of full-size components should be guided by prior stress analysis (computer test simulations) that provide information about the component's response to selected test boundary conditions (heat transfer, temperature gradients, etc.). This procedure should provide reasonably fast discrimination of meaningful results and should require less testing.

8. Turbine Testing to complete the design cycle and demonstrate technological readiness. Turbine testing should be conducted stage by stage and only after sufficient rig testing has verified the reliability (readiness) of a given component.

9. Non-Destructive Evaluation to continue the development of NDE techniques for inspecting components and possibly monitoring their condition over long time periods. This is an important area for advancing brittle design reliability. High frequency ultrasonic scanning and refined X-ray radiography techniques should receive initial emphasis.

The Phase 1 program should provide a well-balanced effort to improve the consistency and predictability of ceramic components in parallel with the development of improved materials, designs and test verification techniques.

SECTION 4

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ABSTRACT

A highlight summary of the work conducted by Westinghouse from July 1971 to June 1976, on the Defense Advanced Research Projects Agency (DARPA) sponsored program, "Brittle Materials Design, High Temperature Gas Turbines," is presented. The Westinghouse portion of the program entitled, "Stationary Turbine Pruject," was concerned with the development of ceramic design and materials technology for large, electric power-generating, combustion turbines. Major incentives for the use of ceramic components in these turbines included significant improvements in the overall efficiency of power conversion through higher operating temperatures and minimum cooling requirements and extended component life through greater resistance to corrosion/erosion with a variety of fuels.

The first stage ceramic stator vane with associated support hardware was chosed as the principal developmental objective. A test demonstration of design concepts and materials feasibility was achieved in a high temperature static rig at a peak vane temperature of 2500°F. Two series of 100 duty cycle testing to represent peaking turbine operation at 0.8 turbine simulation were performed at 2200 and 2500°F, respectively. The three piece vane assembly design concept was confirmed as viable and hot pressed silicon nitride emerged as the best candidate ceramic material for structural turbine applications.

A brief presentation of program background that includes a description of the general development approach and iterative plan of program execution is followed by technical highlights under the two major, interacting program tasks; Material Technology consisting of engineering properties, materials science and non-destructive evaluation (NDE), and Component Development consisting of design and analyses, fabrication, NDE, testing and failure analysis.

Conclusions and recommendations for future ceramic related turbine developments are discussed.

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HIGH TEMPERATURE GAS TURBINE

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Electric Corporation, Pittsburgh, Pennsylvania 15235

Technical Report AMMRC CTR 76-32, Volume I, December, 1976

Contract DAAG 46-71-C-0162, ARPA Order Number 1849

ABSTRACT

A highlight summary of the work conducted by Westinghouse from July 1971 to June 1976, on the Defense Advanced Research Projects Agency (DARPA) sponsored program, "Brittle Materials Design, High Temperature Gas Turbines," is presented. The Westinghouse portion of the program entitled, "Stationary Turbine Project," was concerned with the development of ceramic design and materials technology for large, electric, power components in these turbines include significant improvements in the overall efficiency of power conversion through higher operating temperatures and minimum cooling requirements and extended component life through greater resistance to corrosion/erosion with a variety of fuels.

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A brief presentation of program background that includes a description of the general development approach and iterative plan of program execution is followed by technical highlights under the two major, interacting program tasks; Material Technology consisting of engineering properties, materials science and non-destructive evaluation (NDE), and Component Development consisting of design and analyses, fabrication, NDE, testing and failure analysis.

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